

Analysis of Padding Recovery Time for Sports Helmets

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By

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Abstract

Sports helmets, for games such as football and lacrosse, are typically made with an outer plastic layer and an inner foam layer. They are designed to maximize impact energy attenuation in order to prevent skull fracture and traumatic brain injury. Although the current research focus has shifted to preventing concussions after a singular traumatic impact, no studies have specifically focused on the padding response after multiple successive impacts. This study examined the recovery time for the padding in three youth football helmets and two adult lacrosse helmets. Helmets were impacted while being worn by an Anthropomorphic Test Device (ATD) with sensors installed inside the head to measure kinematics. Impacts were designed to simulate cranial impacts during games. By repeatedly impacting the helmets and analyzing the different kinematic responses, conclusions were drawn regarding the padding recovery time and the optimal waiting period between impacts, both in sports gameplay and in laboratory testing settings. Changes in angular velocity and linear acceleration were determined for each set of impacts. These values were also used to calculate the likelihood of brain injury based on the Head Injury Criteria (HIC) and Brain Injury Criteria (BrIC), two accepted metrics in the field of impact biomechanics. The percent differences from impact to impact were determined and trends were identified for each impact sequence. Based on the results of this study, it was determined that there was generally not a significant difference in the ability of the helmets to attenuate energy after repeated impacts. While there was more variation for lacrosse helmets, both sets of helmets followed this trend. More testing would be needed to further investigate this potential problem before thoroughly concluding that helmets incur no decrease in performance due to repeat impacts.

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Introduction

The safety of American sports helmets is a frequently studied topic. Previous research has focused primarily on determining the padding that most efficiently attenuates impact forces (Gimbel, 2008). However, previous studies have suggested that while the padding in football and lacrosse helmets may be effective for the first impact, it requires time to recover its shape and volume before it is ready for a second impact (McIntosh, 2000). During this recovery period, the helmet is not optimized to reduce the forces experienced by the player's head. If a player is hit while the padding in his helmet is in this pre-compressed state, the helmet will not be as effective in reducing the impact energy transferred to the player's head.

The possibility of reduced helmet efficacy after repeat impacts is especially concerning for youth football players as concussions are more frequent for youth (ages 8-12) than for high school, collegiate, and professional football players (Noble, 2013). In competitions, youth players get concussions at a rate of 6.15 per 1000 athletic exposures but collegiate players get concussions at a rate of 2.5 per 1000 athletic exposures (Noble, 2013). Not only are concussions more frequent in youth players, but youth also make up about 70% of the football players in the United States (Daniel, 2012). Youth football helmets are also of particular interest because the vast majority of current research focuses on helmets for the professional and collegiate levels (Hoshizaki, 2014). Based on this gap in the current research, when testing football helmets, this study focused on youth sizes.

Another sport that is important to consider when discussing concussions is men's lacrosse. In fact, 10.8% of all men's lacrosse players will be diagnosed with a concussion (Noble, 2008). This is the 4th highest rate in all collegiate sports (Noble, 2008). One prior study examined the padding response of adult lacrosse helmets (Caswell, 2002). Therefore, in order to

draw accurate comparisons with the prior work, this study focused on adult sizes when testing lacrosse helmets. Previous studies have done drop testing, however this study utilized a pneumatic ram to simulate gameplay impacts (Caswell, 2002).

Football and lacrosse helmets are both made with an outer layer of plastic and an inner foam layer. Together, these materials dampen the impact shocks which occur during the course of a game. The outer hard plastic layer is typically Acrylonitrile Butadiene Styrene (ABS). Expanded Polypropylene (EPP) and Expanded Polystyrene (EPS) are two common types of inner foam layers used in sports helmets. EPP differs from EPS in that it is a recoverable foam. EPS is non-recoverable, meaning that it is intended for a single impact. This makes it an ideal padding for bicycle and motorcycle helmets. EPP is more ideal for football and lacrosse helmets because it does recover after impact. However, recoverable foams tend to be less efficient energy absorbers than non-recoverable foams (Gimbel, 2008). Another common material used in football and lacrosse helmet padding is Vinyl Nitrile (VN). VN is best for multiple low-energy impacts and degrades slower than EPP (Hoshizaki, 2014).

Studies have considered padding quality in terms of their ability to attenuate linear and rotational velocities and accelerations of the head, but there is a gap in the research regarding the recovery time of the padding after impact (Johnston, 2015). The purpose of this research is to investigate the changes in a helmet's ability to attenuate impact energy after repeated impacts and to draw conclusions regarding the padding recovery time and the optimal waiting period between impacts, both in actual gameplay and in laboratory testing settings.

Methodology

Three youth football helmets (Schutt Youth Air Standard III, Riddell Revolution Speed Youth, Xenith X2E Youth) and two adult lacrosse helmets (Schutt Stallion, Cascade CPX-R)

were placed on Hybrid III Anthropomorphic Test Device (ATD) headforms and were impacted with a pneumatic ram. Table 1 shows each of the helmets that were tested in this study and the types of padding they each have.

Table 1: Tested Helmets

| Sport | Helmet | Picture of Helmet | Picture of Padding | Type of Padding |
|--------------|--------------------------|---|--|---|
| Football | Schutt Air Standard III |  |  | Vinyl Nitrile |
| Football | Xenith X2E |  |  | “Bonnet” System |
| Football | Riddell Revolution Speed |  |  | Vinyl Nitrile and Air Bladders |
| Lacrosse | Cascade CPX-R |  |  | Vinyl Nitrile and Energy Absorbing Structures |
| Lacrosse | Schutt Stallion |  |  | Vinyl Nitrile and Air Bladders |

For the youth football helmets, the headform was designed to mimic the biomechanical response of a 10 year old child. The headform was attached to a Hybrid III 10 year old neckform. The neck was then attached to a mass of 32.1 kg on roller bearings to simulate the mass of a 50th percentile 10 year old child.

For the adult lacrosse helmets, the headform and neckform were Hybrid III 50th percentile male models. A mass of 40.23 kg attached to the base of the neckform to simulate the mass of a 50th percentile male torso. Only the weight of the torso was considered for the adult neckform because the torso is the part of the body that takes the majority of the impact. The full weight of the child was added to the neckform for the football tests because the child has weaker musculature so the effect of the impact will be felt by the whole body instead of just the torso.

Figure 1 shows the testing setup for both rear and side impacts of the football and lacrosse helmets. A diagram of the linear impactor used in this study can be found in Figure 2.

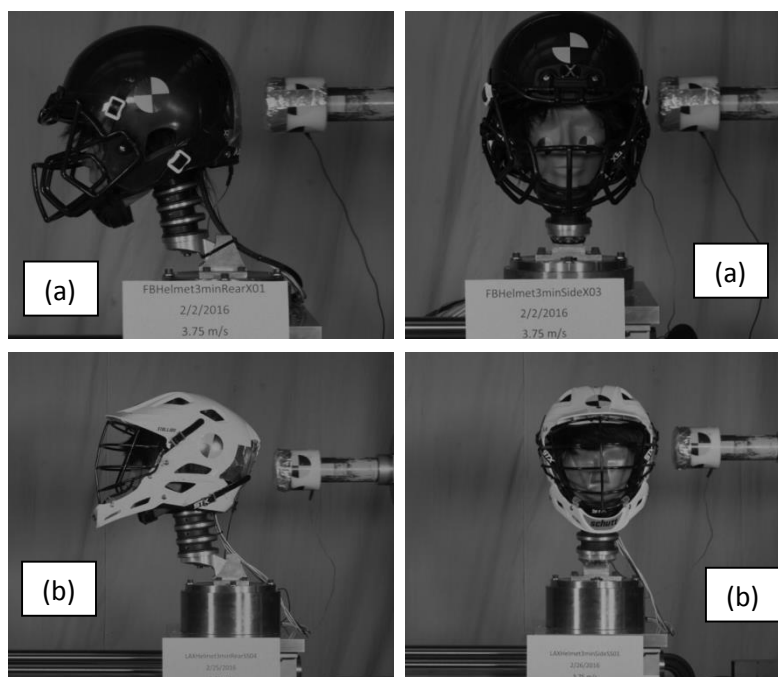


Figure 1: Test Setup for Rear and Side Impact of (a) Football and (b) Lacrosse Helmets

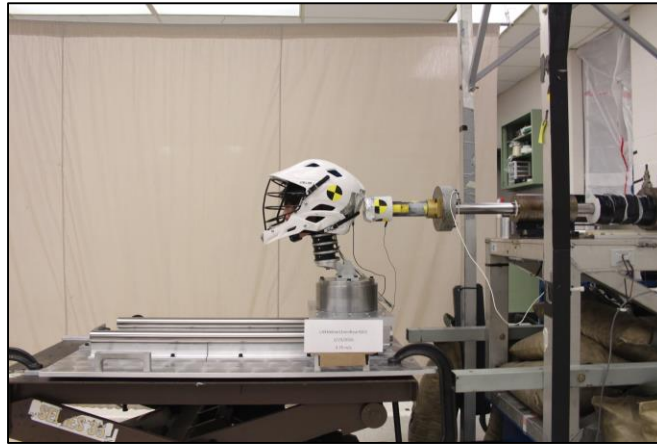


Figure 2: Linear Impactor

Head kinematics data were collected using 3 angular rate sensors (ARS) (DTS ARS Pro, Seal Beach CA) and a three accelerometer array package consisting of piezoelectric accelerometers (Megitt's Endevco, Model #:7246C-2000, Irvine CA). All data was collected at a sample rate of 20,000 Hz. The ARS's were used to measure angular velocity, and the accelerometers were used to measure linear acceleration. Both linear acceleration and angular velocity were directly measured at the Center of gravity (CG) of the headform as shown in Figure 3.

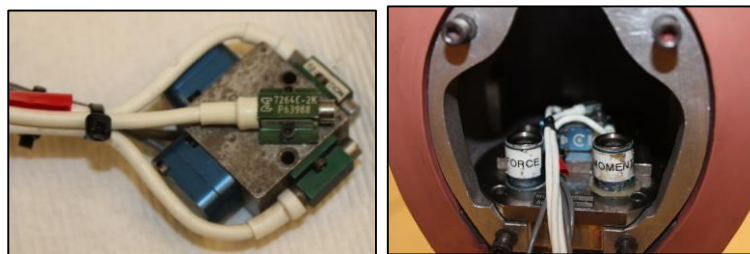


Figure 3: Accelerometer/ARS block located at CG of ATD

For the youth football helmet testing, a load cell (R. A. Denton, INC., Rochester, MI) was placed in the upper neck. It was used to collect data regarding forces and moments in the upper portion of the neck. Figure 4 shows the load cell that was used for this study.

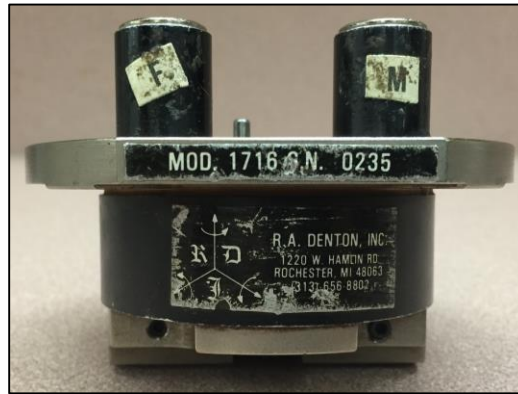


Figure 4: Upper Neck Load Cell for Youth Football Helmet Testing

The helmeted headforms were repeatedly impacted via pneumatic ram at approximately 3.75 m/s. The data were normalized in post-processing to account for any variation in ram speed. The maximum impact speed tested by the National Operating Committee on Standards for Athletic Equipment (NOCSAE), the group that certifies sports helmets, is 5.5 m/s (NOCSAE, 2013). A ram speed of 3.75 m/s was chosen for this study in order to simulate midlevel lacrosse and football impacts. A sample plot of ram velocity over the duration of the impact is shown in Figure 5. In post-processing, Time = 0 sec was chosen to be the point at which the ram struck the helmet.

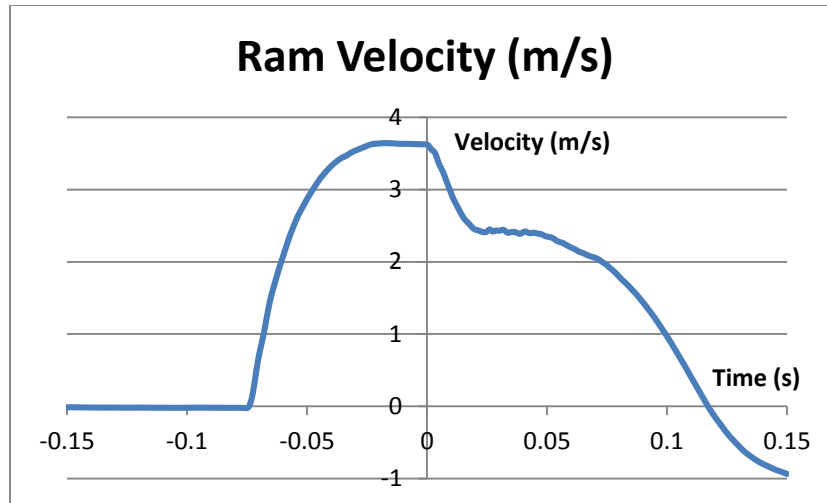


Figure 5: Ram Velocity During Impact

Tests for each helmet included 5 impacts from 2 impact directions (side & rear). The mean time between impacts was 3 minutes and 5 seconds. The standard deviation was 10 seconds. A visual representation of the procedure is depicted in Figure 6.

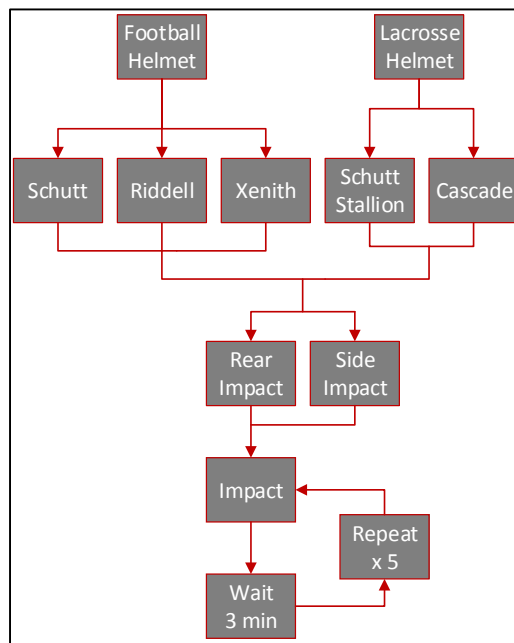


Figure 6: Testing Flowchart

Kinematic data were post processed in DIAdem (National Instruments, Austin TX). Linear acceleration, angular velocity, and force data were all zeroed and then filtered at CFC

1000 according to the SAE J211 standard (Society of Automotive Engineers, 2007). Similarly, the neck moment data were zeroed and filtered at CFC 600, also in accordance with the SAE J211 standard. Next, the data were normalized according to the ram speed. This was done by multiplying the kinematic responses by a normalization factor that was calculated for each set of 5 impacts. As shown in Equation 1, the normalization factor was calculated by taking the average ram speed for a set of impacts and dividing it by the ram speed for the individual impact.

Equation 1: Normalization Factor

$$\text{normalization factor for impact } n = \frac{\sum_{n=1}^5 X_n}{5} * \frac{1}{X_n}$$

Where n = impact number, X = ram speed

After filtering and normalizing the data, MATLAB was used to plot the system responses over the duration of the impact. Resultant accelerations were plotted for each helmet and each impact location (side and rear). The plots contained the resultant acceleration from each of the 5 successive impacts.

Kinematic data collected during the impacts were used to determine the probability of brain injury based on the Brain Injury Criteria (BrIC) and the Head Injury Criteria (HIC). BrIC utilizes maximum rotational velocities to predict brain injury by correlating experimental testing to head & brain finite element models (Takhounts, 2013). The method used to calculate BrIC is shown in Equation 2. In the BrIC equation, ω_x , ω_y , and ω_z are the peak angular velocities in each respective direction. The critical maximum angular velocity values are $\omega_{xc} =$

$66.25 \frac{rad}{sec}$, $\omega_{yc} = 56.45 \frac{rad}{sec}$, and $\omega_{zc} = 42.87 \frac{rad}{sec}$. These values are the same for all ATD's.

They were calculated using the average of the critical values for the cumulative strain damage measure (CSDM) and the maximum principle strain (MPS) risk curves (Takhounts, 2013).

Equation 2: Brain Injury Criterion (BrIC)

$$BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xc}}\right)^2 + \left(\frac{\omega_y}{\omega_{yc}}\right)^2 + \left(\frac{\omega_z}{\omega_{zc}}\right)^2}$$

Where ω_x , ω_y , and ω_z are the peak angular velocities in each direction

HIC was originally developed to assess risk of skull fracture in automobile crashes and is widely used in injury biomechanics research (Hoshizaki, 2014). A HIC value of 1000 has been correlated to an Abbreviated Injury Scale (AIS) rating of 4 (severe), however a HIC value as low as 250 has been correlated with concussions (Hoshizaki, 2014; Viano, 2005). Equation 3 shows how the HIC value was determined (Hoshizaki, 2014).

Equation 3: Head Injury Criterion (HIC)

$$HIC = \max \left((t - t_0) \left[\left(\frac{1}{t - t_0} \right) \int_{t_0}^t a(t) dt \right]^{2.5} \right)$$

Where $(t - t_0) = 15 \text{ ms}$, $a = \text{peak resultant linear acceleration}$

Figure 7 is a plot that shows the probability of injury (in terms of AIS ratings) based on the calculated BrIC number (Takhounts, 2013).

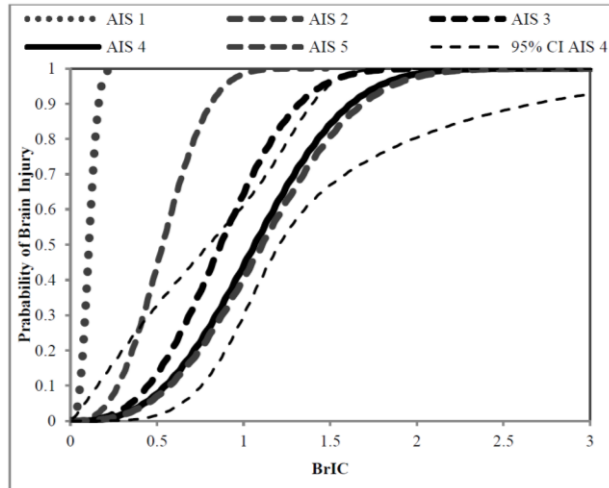


Figure 7: Probability of Brain Injury based on BrIC Value

Results

One example of a resultant acceleration plot for the Xenith football helmet is shown in Figure 8. Figure 9 shows a resultant acceleration plot for the Cascade lacrosse helmet. Additionally, the resultant acceleration of the rear impact of the Schutt Stallion lacrosse helmet is shown in Figure 10 in order to highlight an anomaly in the data that will be noted in the discussion. The remaining resultant acceleration plots can be found in Appendix B for football helmets and Appendix C for lacrosse helmets.

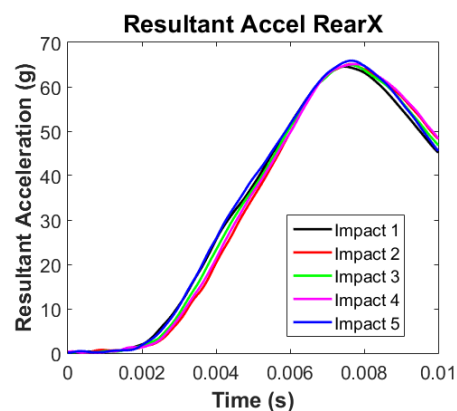


Figure 8: Resultant Acceleration for Rear Impacts of a Xenith Football Helmet

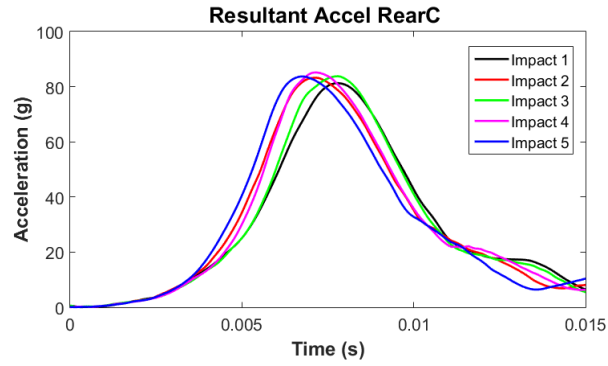


Figure 9: Resultant Acceleration for Rear Impacts of a Cascade Lacrosse Helmet

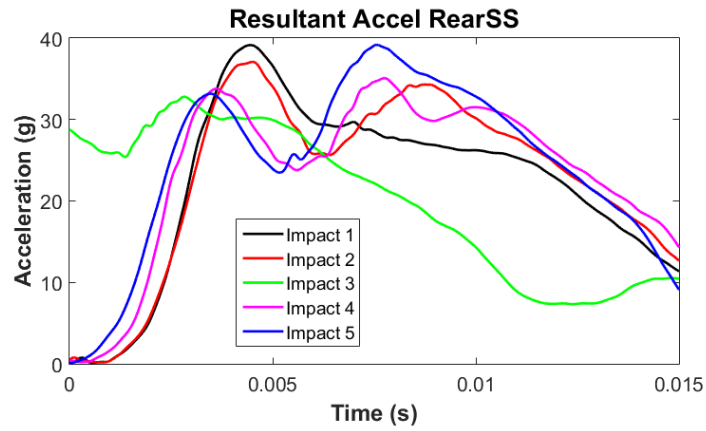


Figure 10: Resultant Acceleration for Rear Impacts of the Schutt Stallion Lacrosse Helmet.

Once the resultant linear accelerations were calculated and plotted for all the tests, the angular velocities were examined. Figure 11 shows the angular velocity in the X, Y, and Z directions for the Xenith football helmet. This figure is representative of the angular velocity responses from the other helmets and impact directions.

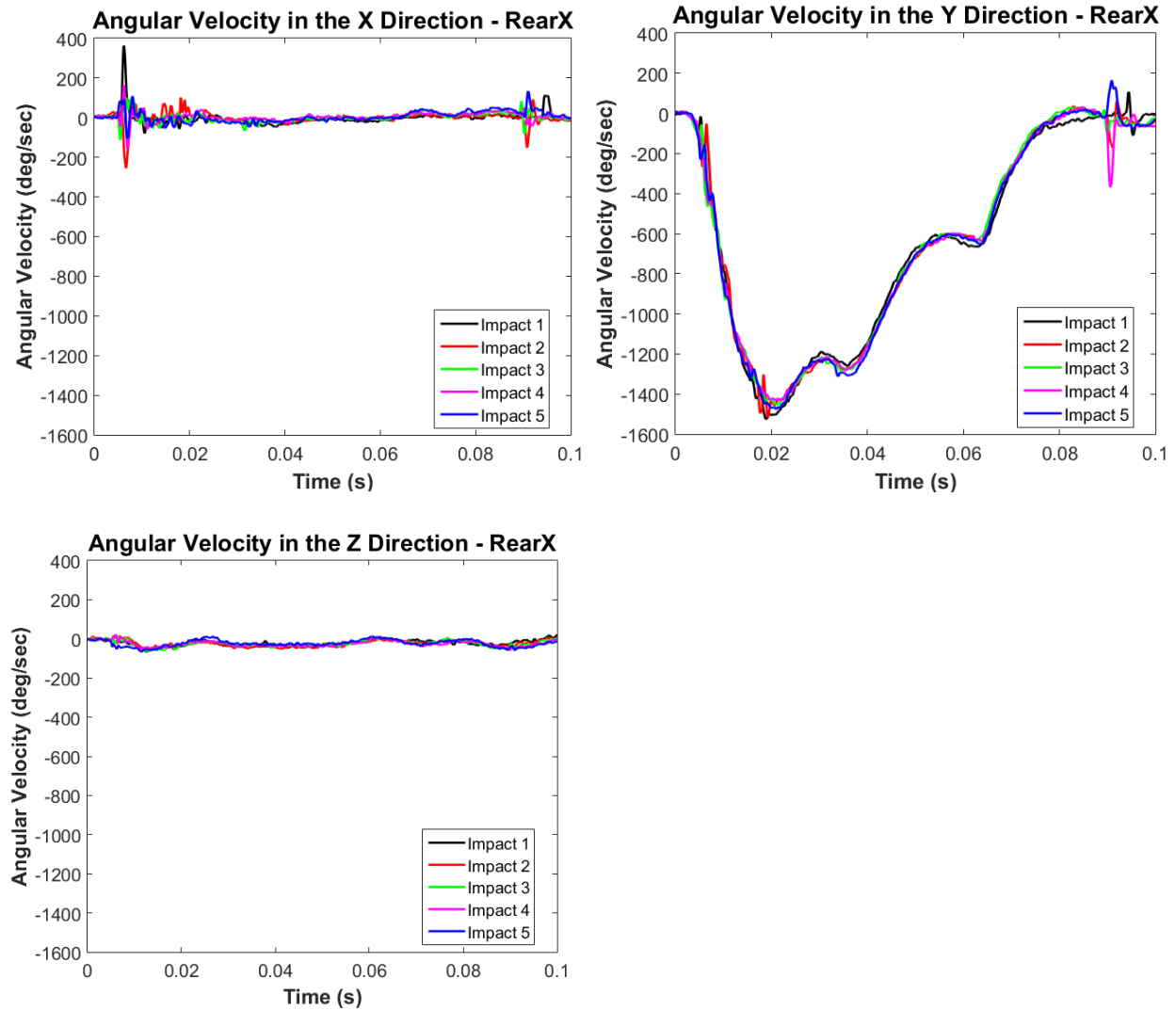


Figure 11: Angular Velocity in the X, Y, and Z Directions for the Rear Impacts of a Xenith Football Helmet

Next, the resultant angular velocities were calculated and graphed. A plot of the resultant angular velocity for the rear impacts of the Xenith football helmet are shown in Figure 12. A plot of the resultant angular velocity for the rear impacts of the Cascade lacrosse helmet are shown in Figure 13. The other lacrosse helmet and the other two football helmets follow a similar trend. The remaining resultant angular velocity plots can be found in Appendix B (football helmet data) and Appendix C (lacrosse helmets data).

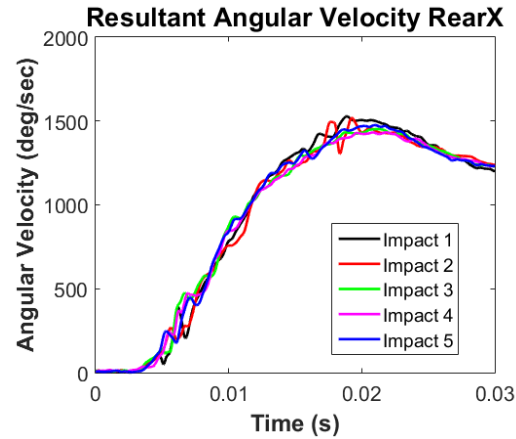


Figure 12: Resultant Angular Velocity for the Rear Impacts of a Xenith Football Helmet

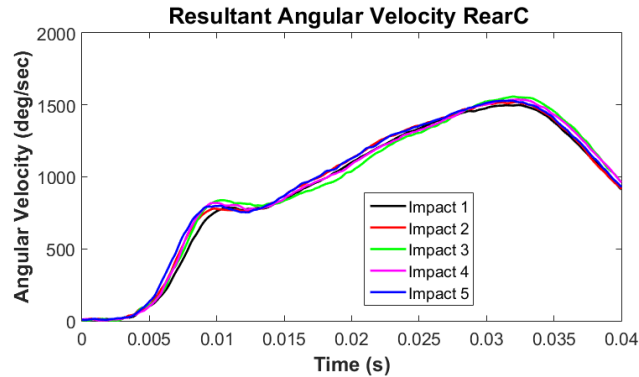


Figure 13: Resultant Angular Velocity for the Rear Impacts of a Cascade Lacrosse Helmet

For the football helmets, the resultant forces and moments in the upper neck were also determined and plotted. Figure 14 shows the force and moment plots for the rear impacts of the Xenith football helmet. These plots are typical of the other force and moment plots for the football helmets. Figure 15 shows the force and moment plots for the side impact of the Riddell football helmet. These results are anomalous because the peak forces and moments change more between impacts. This is visible in the graphs by the separation in the lines. As shown in Figure 14, the remaining force and moment plots had much more consistency from impact to impact. These values were not determined for the lacrosse helmets because the adult neckform used in these tests was not equipped with a load cell.

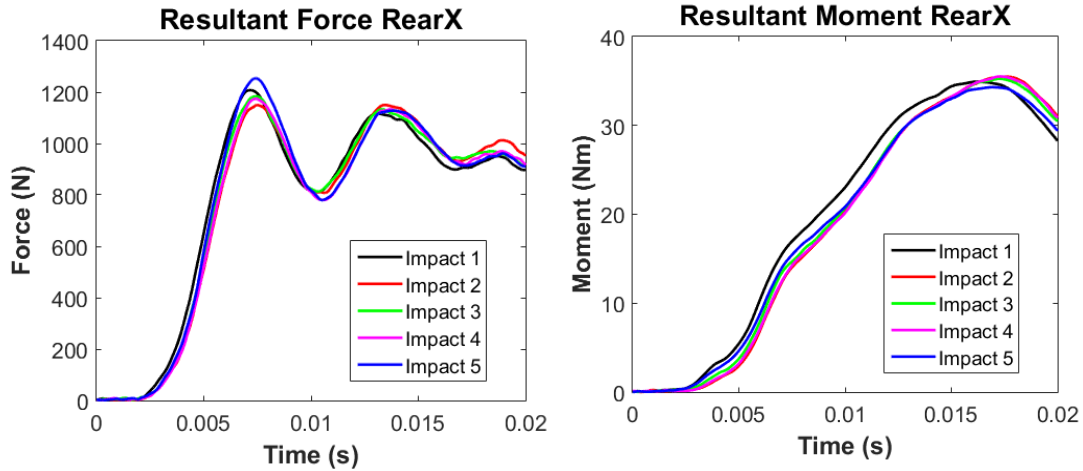


Figure 14: Resultant Force and Moment Plots for Rear Impacts of a Xenith Football Helmet

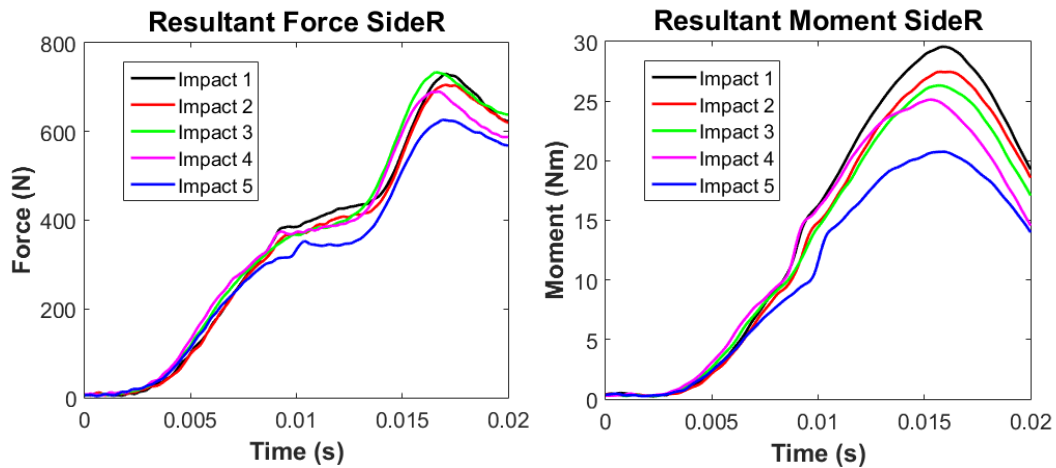


Figure 15: Resultant Force and Moment Plots for Side Impacts of a Riddell Football Helmet

After determining all of the resultant data, maximums were taken of each of those resultants. The maximum values were then plotted, again with each plot including data from the 5 impacts involved in that particular test. The maximum values were plotted as single points and a trendline was added to the plots for each of the helmets.

Three analyses methods were used on the maximum resultant data. First, the percent differences between the 1st and 5th impacts were determined. A sample calculation is shown in

Equation 4. Next, average percent difference was calculated as shown in Equation 5. Finally, a Coefficient of Variance (CV) was calculated as shown in Equation 6.

Equation 4: Percent Difference from Impact 1 to Impact 5

$$\text{Percent Difference from Impact 1 to Impact 5} = \frac{X_5 - X_1}{X_1}$$

Equation 5: Average Percent Difference

$$\text{Average Percent Difference} = \frac{\sum_{n=2}^5 \left(\frac{X_n - X_1}{X_1} \right)}{4}$$

Equation 6: Coefficient of Variance (CV)

$$CV = \frac{\sigma}{\mu}$$

Where σ = sample standard deviation , μ = average

The CV was calculated in order to determine repeatability of the tests. Based on common practice within the field of injury biomechanics, CV's less than 5% were considered repeatable. If a test sequence had a CV that was greater than 5%, that meant that the maximum values were significantly different. CV scores were analyzed based on common practice within the field of injury biomechanics (Rhule, 2005). These metrics are show in Table 2.

Table 2: Assessment of CV Scores

| CV Score | Assessment |
|------------|-----------------------|
| 0 – 5% | Excellent |
| > 5% – 8% | Good |
| > 8% – 10% | Marginal (Acceptable) |
| > 10% | Poor (Unacceptable) |

The maximum value plots and trend lines were then used to determine in what way the maximum values within an impact sequence differed from one another. The maximum value plots and the percent difference tables for the youth football helmets can be found in Figure 12-Figure 19 and Table 3-Table 6. The maximum value plots and the percent difference tables for the adult lacrosse helmets can be found in Figure 20-Figure 21 and Table 7-Table 8. In the percent difference tables, green coloring indicates a negative percentage, pink coloring indicates a positive percentage, and dark pink coloring indicates a positive percentage that is greater than 5%.

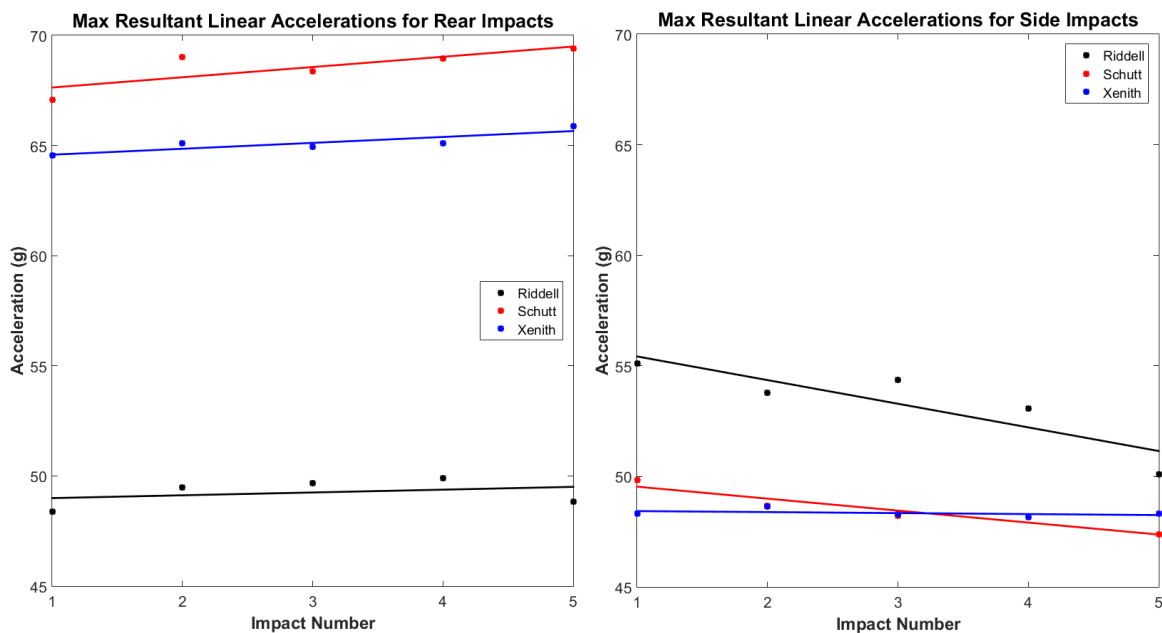


Figure 16: Max Resultant Linear Acceleration Plots for Youth Football Helmets

Table 3: Repeatability and % Difference Data for Max Resultant Linear Acceleration of Youth Football Helmet Impacts

| Direction of Impact | Rear | | | Side | | |
|--|---------|--------|--------|---------|--------|--------|
| Helmet | Riddell | Schutt | Xenith | Riddell | Schutt | Xenith |
| % Difference between Impact 1 and Impact 5 | 0.9% | 3.5% | 2.1% | -9.1% | -4.9% | 0.0% |
| Average % Difference from Impact 1 | 2.2% | 2.8% | 1.1% | -4.1% | -3.5% | 0.1% |
| Coefficient of Variance | 1.3% | 1.3% | 0.7% | 3.6% | 1.9% | 0.4% |

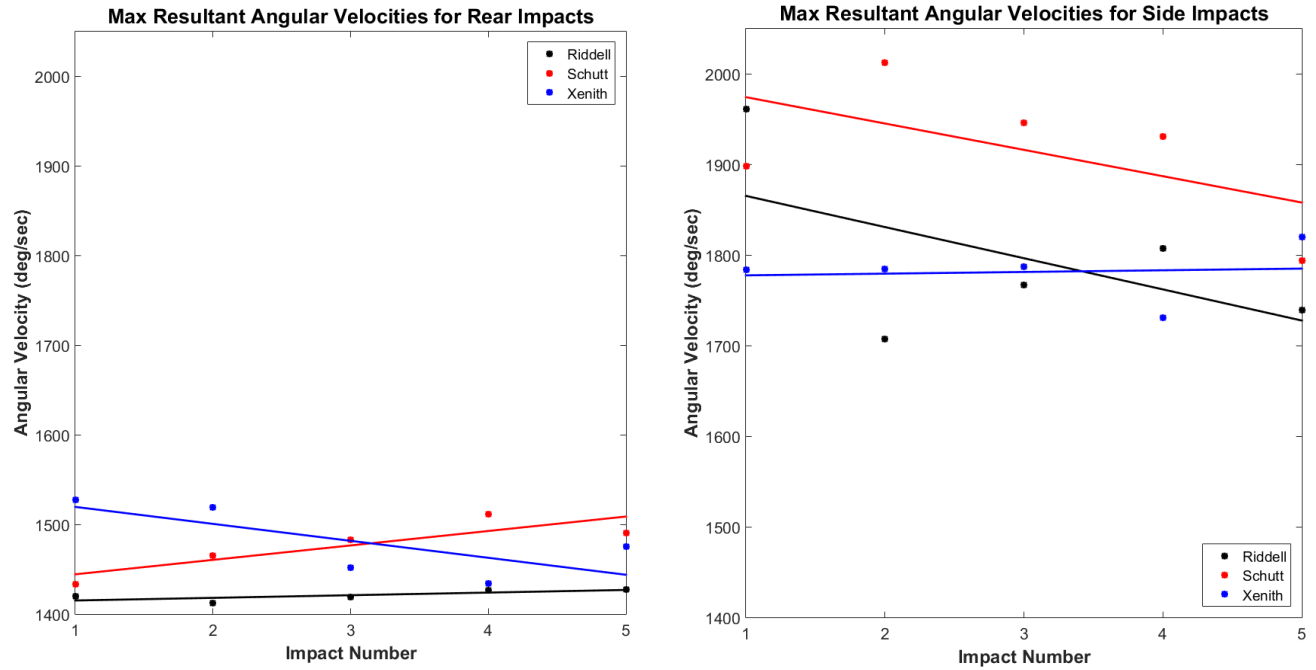


Figure 17: Max Resultant Angular Velocity Plots for Youth Football Helmets

Table 4: Repeatability and % Difference Data for Max Resultant Angular Velocity of Youth Football Helmet Impacts

| Direction of Impact | Rear | | | Side | | |
|--|---------|--------|--------|---------|--------|--------|
| | Riddell | Schutt | Xenith | Riddell | Schutt | Xenith |
| % Difference between Impact 1 and Impact 5 | 0.5% | 4.0% | -3.4% | -11.3% | -5.5% | 2.0% |
| Average % Difference from Impact 1 | 0.1% | 3.8% | -3.8% | -10.5% | 1.2% | -0.2% |
| Coefficient of Variance | 0.4% | 2.0% | 2.8% | 5.5% | 4.2% | 1.8% |

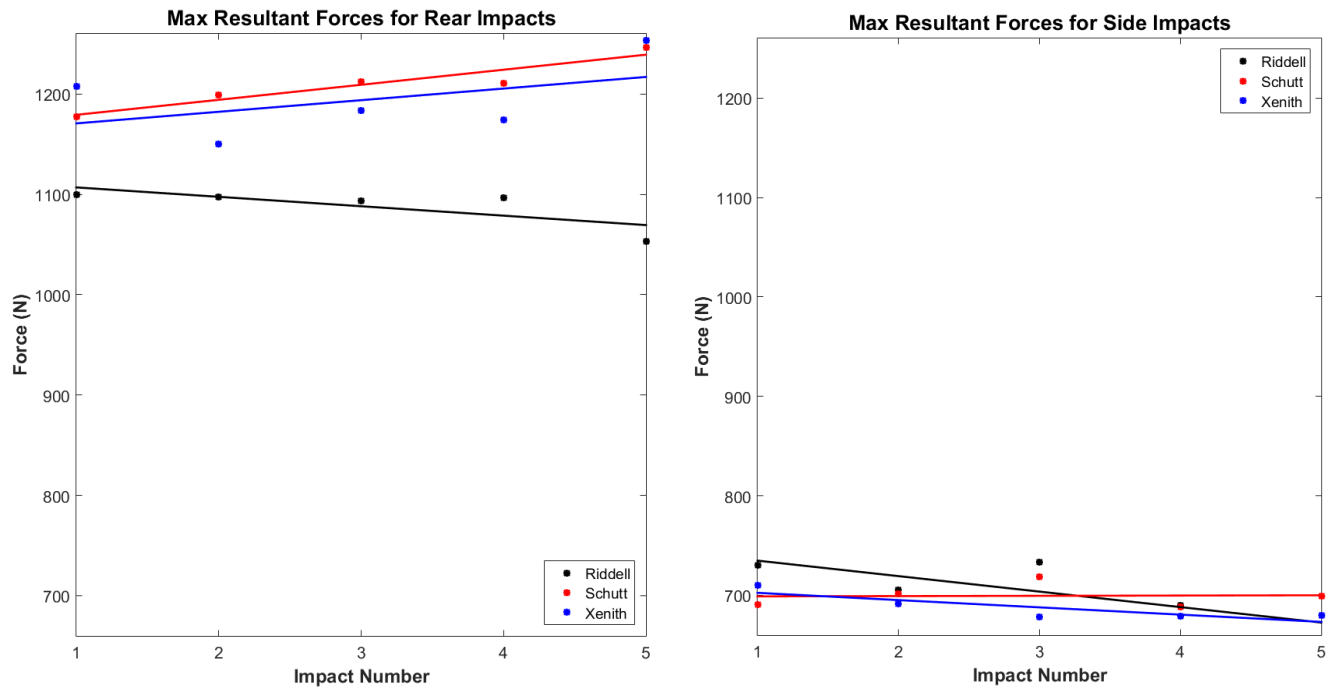


Figure 18: Max Resultant Force Plots for Youth Football Helmets

Table 5: Repeatability and % Difference Data for Max Resultant Forces of Youth Football Helmet Impacts

| Direction of Impact | Rear | | | Side | | |
|--|---------|--------|--------|---------|--------|--------|
| Helmet | Riddell | Schutt | Xenith | Riddell | Schutt | Xenith |
| % Difference between Impact 1 and Impact 5 | -4.2% | 5.9% | 3.8% | -9.6% | 1.2% | -4.3% |
| Average % Difference from Impact 1 | -1.3% | 3.4% | -1.5% | -4.5% | 1.6% | -4.0% |
| Coefficient of Variance | 1.8% | 2.1% | 3.3% | 4.3% | 1.7% | 2.0% |

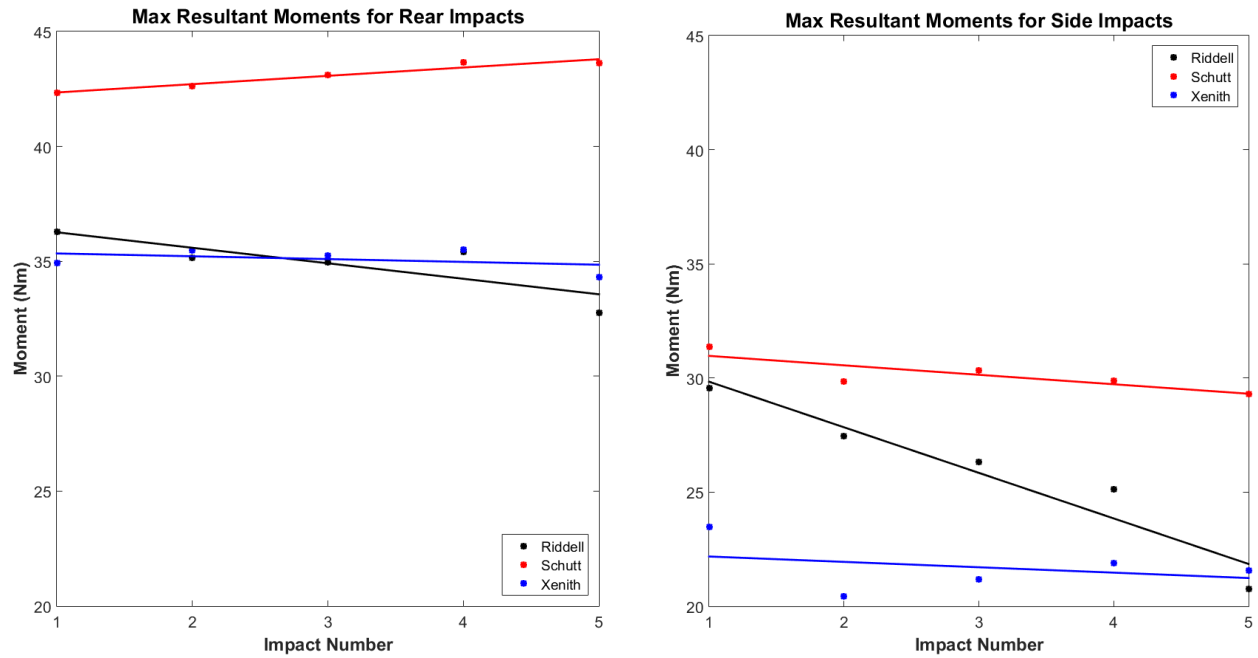


Figure 19: Max Resultant Moment Plots for Youth Football Helmets

Table 6: Repeatability and % Difference Data for Max Resultant Moments of Youth Football Helmet Impacts

| Direction of Impact | Rear | | | Side | | |
|--|---------|--------|--------|---------|--------|--------|
| Helmet | Riddell | Schutt | Xenith | Riddell | Schutt | Xenith |
| % Difference between Impact 1 and Impact 5 | -9.7% | 3.1% | -1.8% | -29.8% | -6.7% | -8.1% |
| Average % Difference from Impact 1 | -4.7% | 2.2% | 0.6% | -15.7% | -4.9% | -9.4% |
| Coefficient of Variance | 3.7% | 1.4% | 1.4% | 12.7% | 2.6% | 5.2% |

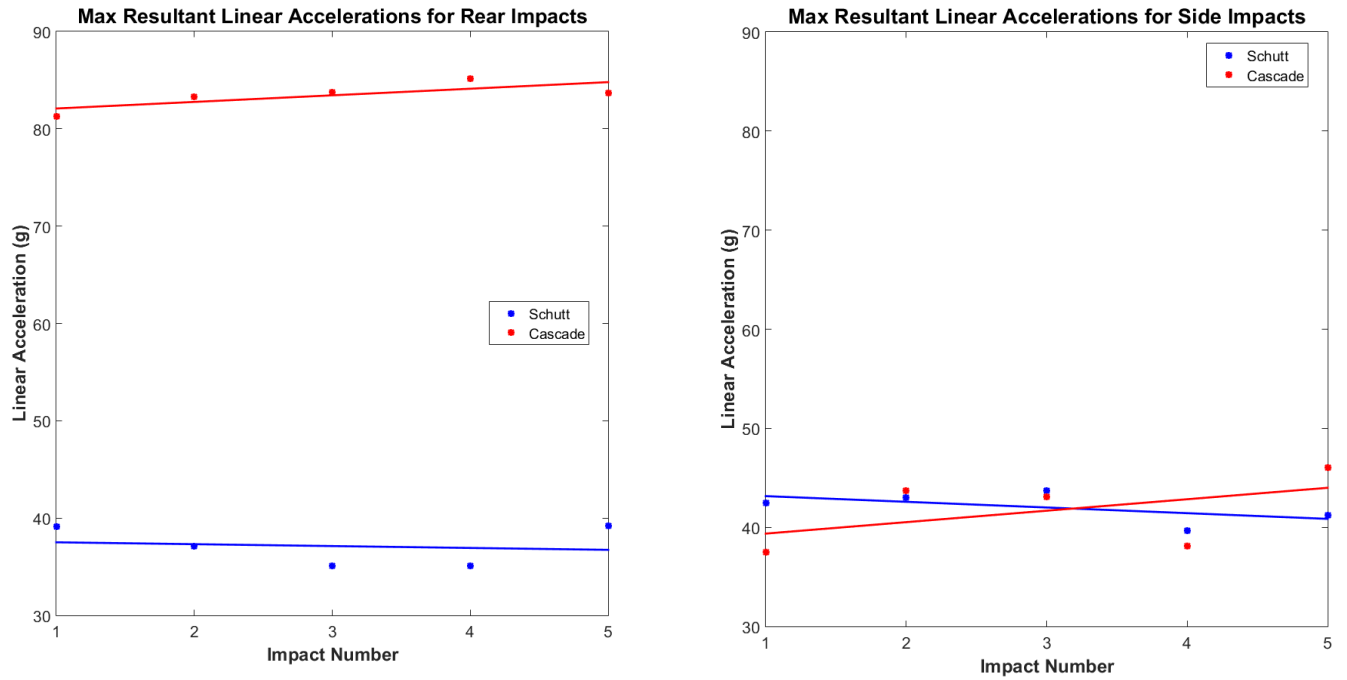


Figure 20: Max Resultant Linear Acceleration Plots for Adult Lacrosse Helmets

Table 7: Repeatability and % Difference Data for Max Resultant Linear Acceleration of Adult Lacrosse Helmet Impacts

| Direction of Impact | Rear | | Side | |
|--|--------|---------|--------|---------|
| Helmet | Schutt | Cascade | Schutt | Cascade |
| % Difference between Impact 1 and Impact 5 | 0.1% | 3.0% | -2.8% | 22.9% |
| Average % Difference from Impact 1 | -6.5% | 3.3% | -1.3% | 14.0% |
| Coefficient of Variance | 5.5% | 1.7% | 3.8% | 8.9% |

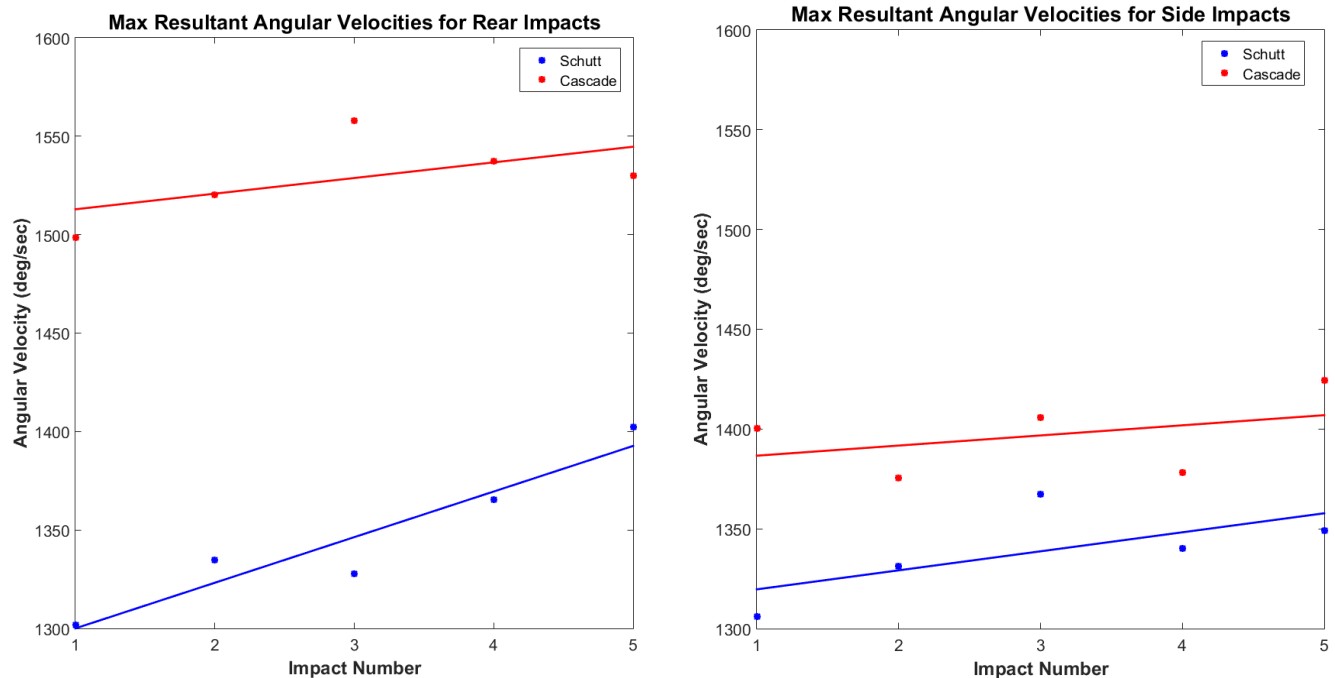


Figure 21: Max Resultant Angular Velocity Plots for Adult Lacrosse Helmets

Table 8: Repeatability and % Difference Data for Max Resultant Angular Velocity of Adult Lacrosse Helmet Impacts

| Direction of Impact | Rear | | Side | |
|--|--------|---------|--------|---------|
| Helmet | Schutt | Cascade | Schutt | Cascade |
| % Difference between Impact 1 and Impact 5 | 7.7% | 2.1% | 3.3% | 1.7% |
| Average % Difference from Impact 1 | 4.3% | 2.5% | 3.1% | -0.3% |
| Coefficient of Variance | 2.9% | 1.4% | 1.7% | 1.5% |

After calculating and analyzing the maximum values, the HIC and BrIC values were calculated for each of the 5 impacts of each test. These values were also plotted with trendlines for each set of impacts. Figure 22 and Figure 23 show the plots of the BrIC values of the football and lacrosse helmets, respectively. Figure 24 and Figure 25 show the plots of the HIC values for football and lacrosse helmets, respectively. The percent differences and CV's of the BrIC and HIC values were also determined for each of the impacts as compared to the first impact. These percentages are shown in Table 9 - Table 12.

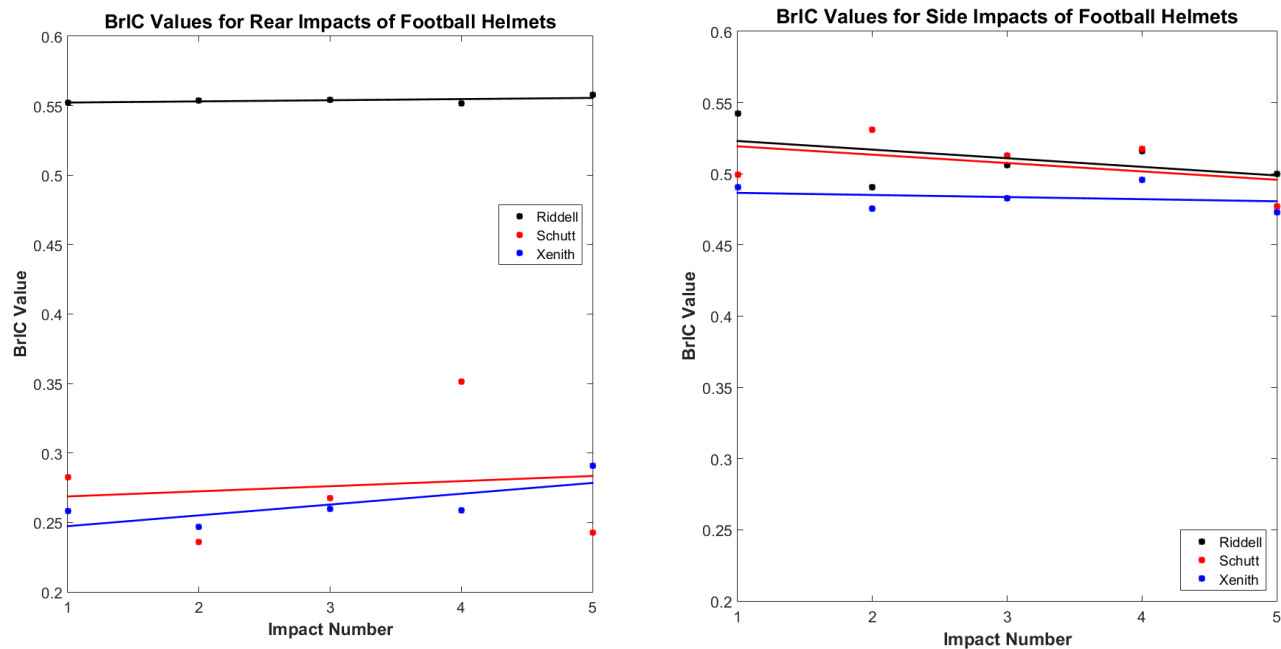


Figure 22: BrIC Value Plots for Rear and Side Impacts of Youth Football Helmets

Table 9: Repeatability and % Difference Analysis for BrIC Values of Youth Football Helmet Impacts

| Direction of Impact | Rear | | | Side | | |
|--|---------|--------|--------|---------|--------|--------|
| Helmet | Riddell | Schutt | Xenith | Riddell | Schutt | Xenith |
| % Difference between Impact 1 and Impact 5 | 0.9% | -13.9% | 12.7% | -7.9% | -4.5% | -3.6% |
| Average % Difference from Impact 1 | 0.3% | -2.7% | 2.3% | -7.3% | 2.0% | -1.8% |
| Coefficient of Variance | 0.4% | 16.7% | 6.3% | 3.9% | 4.0% | 2.0% |

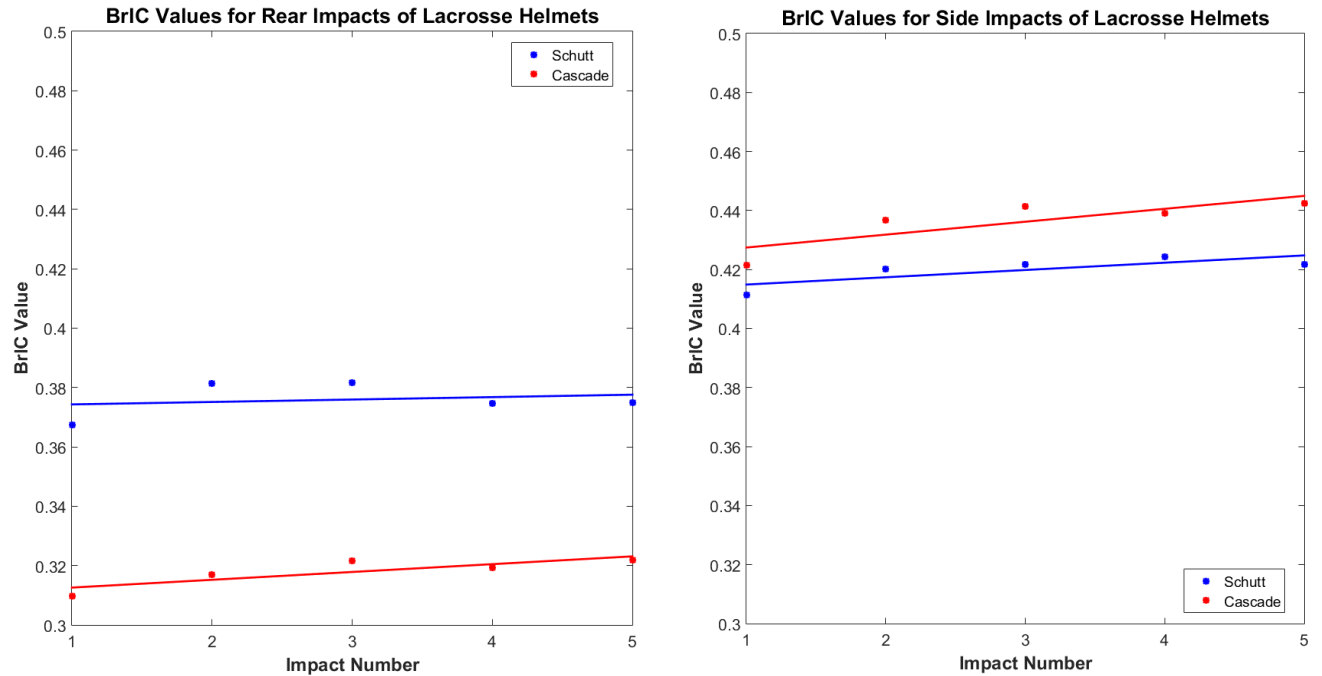


Figure 23: BrIC Value Plots for Rear and Side Impacts of Adult Lacrosse Helmets

Table 10: Repeatability and % Difference Analysis for BrIC Values of Adult Lacrosse Helmet Impacts

| Direction of Impact | Rear | | Side | |
|--|--------|---------|--------|---------|
| Helmet | Schutt | Cascade | Schutt | Cascade |
| % Difference between Impact 1 and Impact 5 | 2.0% | 3.9% | 2.5% | 4.9% |
| Average % Difference from Impact 1 | 2.9% | 3.3% | 2.6% | 4.3% |
| Coefficient of Variance | 1.6% | 1.6% | 1.2% | 1.9% |

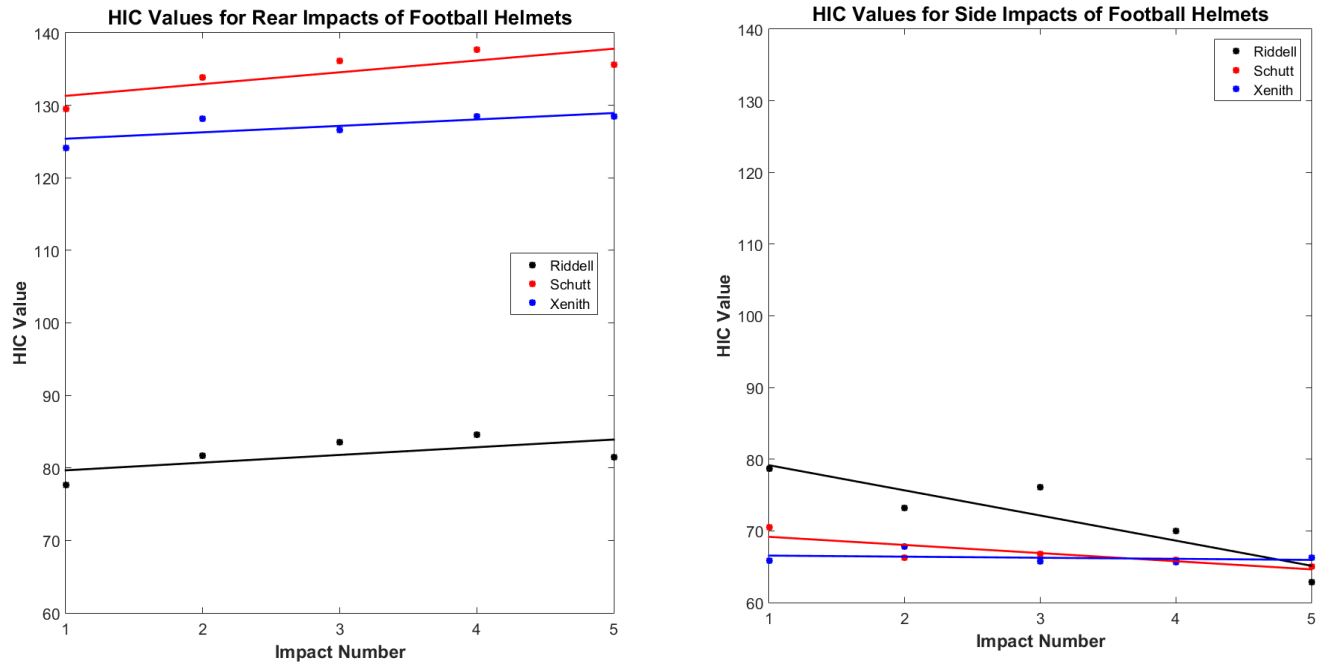


Figure 24: HIC Value Plots for Rear and Side Impacts of Youth Football Helmets

Table 11: Repeatability and % Difference Analysis for HIC Values of Youth Football Helmet Impacts

| Direction of Impact | Rear | | | Side | | |
|--|---------|--------|--------|---------|--------|--------|
| Helmet | Riddell | Schutt | Xenith | Riddell | Schutt | Xenith |
| % Difference between Impact 1 and Impact 5 | 4.9% | 4.8% | 3.5% | -20.2% | -7.8% | 0.5% |
| Average % Difference from Impact 1 | 6.7% | 4.9% | 3.0% | -10.4% | -6.4% | 0.7% |
| Coefficient of Variance | 3.2% | 2.3% | 1.5% | 8.5% | 3.2% | 1.3% |

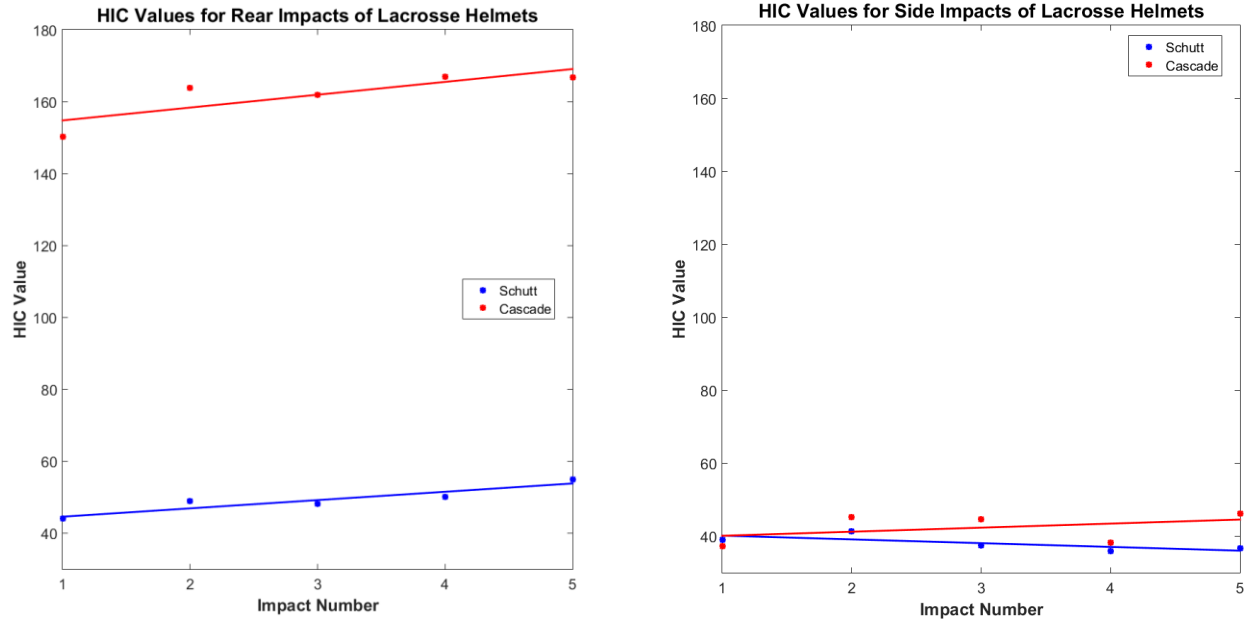


Figure 25: HIC Value Plots for Rear and Side Impacts of Adult Lacrosse Helmets

Table 12: Repeatability and % Difference Analysis for HIC Values of Adult Lacrosse Helmet Impacts

| Direction of Impact | Rear | | Side | |
|--|--------|---------|--------|---------|
| Helmet | Schutt | Cascade | Schutt | Cascade |
| % Difference between Impact 1 and Impact 5 | 24.8% | 10.9% | -6.2% | 24.4% |
| Average % Difference from Impact 1 | 14.8% | 9.6% | -3.0% | 17.2% |
| Coefficient of Variance | 8.0% | 4.2% | 5.8% | 10.1% |

Discussion

Football Helmet Responses

In examining the plots of headform resultant linear acceleration for football helmets it is evident that the successive impacts did not result in much change in acceleration. The coefficients of variance (CV's) for the maximum resultant accelerations are all less than 5% which means that the data are repeatable. This means that the change in acceleration from impact to impact is not statistically significant. This conclusion is further supported by the calculations of the percent differences between the 1st and 5th impacts which are less than 5% for all football helmet repeat impact tests. The average percent differences from impact 1 show a similar trend with all of the impact sequence having less than 5% average difference.

The maximum resultant acceleration trendline plots show either negative slopes or only slightly positive slopes. Negative slopes are not as much of a concern for the safety of the football players because they indicate a lower risk with successive hits due to better energy attenuation of the later hits. This may have been caused by changes in helmet positioning on the headform between impact or the padding becoming conditioned to the shape of the headform over the course of the impacts. Negative slopes may have also been caused by random variation in the data. One interesting thing to note about the maximum acceleration plots is the fact that the magnitudes of the acceleration responses for the rear impact of the Riddell helmet are significantly lower than those of the rear impacts for the other two football helmets. This means that the Riddell helmet was consistently better able to attenuate energy during a rear impact when compared to the Schutt and Xenith helmets. This was likely due to the different padding; the Riddell helmet used air bladders with Vinyl Nitrile (VN) padding instead of just VN padding or a "bonnet" system.

The resultant angular velocity plots for the youth football helmets show more random variation than the resultant linear acceleration plots, but each of the repeat impacts were still very consistent with one another. The greater variation in data among the side impact tests may be due to a loose sensor during testing. It may also be due to the fact that the Hybrid III ATD was designed primarily for frontal collisions, not necessarily for side or rear impacts (Foster, 1977). Again, in examining the maximum value trendline plots, the slopes of the trendlines were either negative or only slightly positive which suggests that the helmets' ability to attenuate impact energy was not significantly decreasing with the repeated impacts. The percent differences in maximum angular velocities between the 1st and 5th impacts were all less than 5%. The anomaly in the CV data was the side impact of the Riddell helmet, which had a CV greater than 5%. However, this is not a concern because that impact sequence had percent differences of less than -10%. This means that the peak resultant velocity for that set of impacts decreased by about ten percent after the repeat impacts.

An interesting anomaly in regards to the angular velocities is that the resultant magnitudes were higher for the side impacts than for the rear impacts. For the football helmets, the resultant linear acceleration, resultant force, and resultant moment were all higher for the rear impacts. This anomaly is thought to be caused by the location of impact compared to the location of the CG. Prior to impact, the pneumatic ram was positioned so that it would hit the helmeted headform as close as possible to the CG without impacting the facemask. Any slight shift away from the CG could have caused an increase in angular velocity for the side impacts. Another factor that may have contributed to this anomaly is the design of the Hybrid III neckform. The neckform was designed for impacts to the frontal and rear plane, so it may not be as accurate for side impacts (Foster, 1997).

For the youth football helmets, the load cell in the neckform allowed for the collection and analysis of force and moment data. The time plots of the resultant forces show consistent data with only the Riddell helmet showing some variations in the peak values. The maximum resultant plots show that during the Riddell impacts the force experienced by the neckform actually slightly decreased with each successive hit. Again the plots of the maximum forces show how the Riddell helmet stands out from the other two helmets. For the rear impacts, the maximum forces for the Riddell helmet trend downwards and are approximately 100 Newtons less than the forces from the Xenith and Schutt impacts. This may be due to variation in kinematic response between tests. For the side impacts, the forces of the Riddell impacts trended downwards while the impacts to the other two helmets had slightly positive slopes. For all of the maximum force data, CV's of less than 5% indicate that the data were repeatable. For the rear impact of the Schutt football helmet, the percent difference between the 1st and 5th impacts was greater than 5% which indicates that the helmet's ability to attenuate force may have significantly changed between the 1st and 5th impacts. However, since the CV was less than 5% for this impact sequence, it is still reasonable to conclude that there was no significant change in the upper neck response after repeated impacts.

The moment plots for the youth football helmets show less consistency than the other time plots. For all three helmets, the moment plots for the side impacts showed more variability than the moment plots for the rear impacts. The plots for the Riddell helmet show a distinctive decrease in moment with each successive impact and the side impact shows more of a decrease than the rear impact. For the side impact of the Riddell helmet, the CV is 12.7% which indicates a significant change in the moment from impact to impact. However, in looking at the trendline and the percent differences, it is clear that the moment is actually decreasing with each

successive impact. The other two helmets show some variation but it is more random than with the Riddell helmet, meaning that at the upper neck there is not a clear increase or decrease in moment with each successive impact. The CV for the side impact of the Xenith helmet is greater than 5% which suggests variability in the data. In looking at the trendline, it appears that there is data variation without a large upward or downward trend. This means that there was probably just some variation in the neckform response and no real difference in the moment. The reason that the moments decreased for the Riddell helmet and not the other two helmets may be because of the padding used in the Riddell helmet. The Riddell helmet has air bladders that cushion the headform in addition to the Vinyl Nitrile (VN) padding. These extra air bladders may cause the helmet to attenuate the impact energy more effectively than helmets with other padding materials. This causes a decrease in neck kinetic response. In examining the maximum resultant moment plot, the Schutt helmet had higher magnitudes than the other two football helmets. This may be because the Schutt helmet just used VN padding instead of a “bonnet” system or VN padding and air bladders.

Lacrosse Helmet Responses

The resultant linear acceleration plots for the lacrosse helmets show more variation than the plots for the football helmets. For the rear impact of the Schutt Stallion helmet, there are two peaks. This is likely due to the fin design on the back of the helmet. The 3rd impact is anomalous for this set of impacts. Although there was no noticeable difference in the video replays of the helmet response for the 3rd impact and the responses for the other four impacts, this was probably because the ram got caught on the fin. The rear impact for the Cascade helmet showed some variation in the time history but not much difference in the peak magnitudes of each impact. Both of the side impacts showed some variation in the magnitude with the acceleration of the Cascade helmet generally trending up and the Schutt Stallion helmet generally trending down.

These trends are verified by looking at the maximum resultant acceleration plot. The maximum resultant acceleration magnitudes matched the magnitudes found in a previous study that conducted repeat drop tests of lacrosse helmets (Caswell, 2002). The one exception was the rear impact of the Cascade helmet which had resultant accelerations approximately twice as large as the other lacrosse helmet impacts. This was likely due to the arrangement of the energy absorbing structures in the back of the helmet. Despite this anomaly, the resultant accelerations for both the football and the lacrosse helmets fell well below 200g which has been used to predict traumatic brain injury (Caswell, 2002). In fact, all peak resultant linear accelerations were less than 100g's. However, successive subconcussive impacts may still impair neurological function over time (Caswell, 2002).

It is interesting to note that Caswell's data consistently showed helmets' decreased ability to attenuate impact energy after repeated impacts. That study analyzed data based on the Gadd Severity Index (GSI). GSI is a head injury metric that uses resultant linear acceleration data, similar to HIC. The study found that rear drops had GSI increases from 22.6% to 71.7% (Caswell, 2002). Caswell's findings differ from the data found in this study because despite using different metrics, this study did not find such conclusive increases in kinematic response after repeated impacts. This difference could be due to the difference in helmets tested or the different test method. Caswell's study used a drop tower and helmets from the early 2000's while this study used a pneumatic ram with helmets that were released in 2014 (Caswell, 2002).

In examining the angular velocity time series and the maximum angular velocity trendline plots for the lacrosse helmets, it is evident that the repeat impacts showed little variation in most cases, with each sequence trending slightly upward. This is further supported by the average percent differences which are all positive numbers but all less than 5%. The

percent difference between impact 1 and impact 5 is approximately 7% for the rear impact of the Schutt Stallion helmet. This difference can be seen in the maximum resultant plot as a steeper slope than is typical of the other trendlines. This anomaly is possibly due to the fin as noted in the discussion of the linear acceleration trends. Also like the maximum linear acceleration plot for rear impacts, the magnitude of the Cascade helmet response was significantly greater than that of the Schutt Stallion helmet. Again, this may have to do with the padding arrangement in the back of the Cascade helmet.

Injury Criteria

In looking at the BrIC values for the football helmets, the side impacts have higher BrIC values than the rear impacts. This makes sense because the side impacts also had greater maximum resultant angular velocities, which are used to calculate the BrIC. The main anomaly in the BrIC value plots is for the rear impact of the Xenith helmet. This impact had low angular velocities compared to the other two helmets, yet it has a much higher BrIC value. This may be due to the difference in the way maximum resultant values and BrIC values are calculated. The BrIC value accounts for the maximum angular velocity in each direction irrespective of their time points. This means that it may account for data that the maximum resultant overlooks. For example, for a side impact, the BrIC value may account for peaks in the y-direction while the maximum resultant may not. The CV for the rear impact of the Schutt helmet is high which makes sense when looking at the trendline plot. There is a lot of variation in the data despite the fact that the trendline is relatively flat. This variation is likely also due to extra peaks accounted for in the BrIC value calculation. The rear impact of the Xenith helmet, on the other hand, has a CV great than 5% but it also has a trendline with a clearly positive slope. This means that there was a significant increase in the BrIC number for that impact sequence. The increase in BrIC number for the Xenith helmet may have been due to the helmet, and specifically the “bonnet”

system padding, shifting on the headform over the course of the impacts. This is not too much of a concern, however, because as mentioned previously the BrIC values for the side impacts were higher than those of the rear impacts.

For the HIC value plots of the football helmets, again, the rear impact of the Xenith helmet is the anomaly. This time, it consistently has a lower HIC value than the rear impacts of the other two helmets. This makes sense because the HIC value is based on the maximum resultant linear acceleration. The linear regression lines of best fit for the HIC values all follow the same general trend as those of the linear acceleration. For these plots, the only impact sequence with a CV greater than 5% was the side impact sequence of the Riddell helmet, meaning that there was a significant difference between these points. In this case, the HIC value actually decreased with successive impacts. Again, this makes sense because the maximum resultant linear acceleration also seemed to be decreasing for that helmet.

The BrIC value plots for the lacrosse helmets are similar to those of the football helmets in that they follow the same trends as the resultant angular velocity for the side impacts and are reversed for the rear impacts. That is, for the rear impacts of the lacrosse helmets, the Cascade helmet had a higher resultant angular velocity than the Schutt Stallion helmet. However, the Cascade helmet consistently had a lower BrIC value. All the BrIC plots for the lacrosse helmets had percent differences, average percent differences, and CV's of less than 5%. This suggests that the BrIC values did not significantly change from impact to impact.

The HIC values for the lacrosse helmets, on the other hand, did significantly change with successive impacts. For the side impact of the Schutt Stallion helmet, the coefficient of variance was greater than 5%, suggesting some variability in the data. However, based on the percent

difference and the average percent difference, that variability was not a concern for this study because the HIC values decreased with successive impacts. For the rear impact of the Cascade lacrosse helmet, the percent difference and average percent difference were greater than 5% but the CV was less than 5% suggesting that there was not enough variability in the data to be significant. For the rear impact of the Schutt Stallion helmet and the Side Impact of the Cascade helmet, all three metrics were greater than 5% suggesting a significant change from impact to impact. In this case, the positive slopes of the linear regression best fit lines show that the HIC values increased with repeated impacts. Despite this, the slope of those lines was so small that at those rates it would take at least 30 more impacts to raise the HIC number by 100. At that point, the HIC values for the rear impact of the Cascade helmet would be near 250, well below the HIC value of 1000 that has been associated with AIS level 4 injuries (Hoshizaki, 2014).

Limitations and Sources of Error

Limitations and sources of error for this study include the fact that the behaviors of the ATD's do not perfectly model real life biomechanical reactions. The ATD's are accepted in the field of injury biomechanics and have been correlated with the kinematic responses of the human body, specifically with the head and neck. They were designed specifically for high energy, short duration impacts such as those used in this study. However, they were designed for frontal impacts, not for the rear and side impacts used in this study. While these ATD's are accepted as biofidelic, they are not perfect substitutes for a living human being. Additionally, for the youth football helmets, the mass attached to the base of the neckform was the entire mass of a 50th percentile child, instead of just the mass of the torso. This is a limitation of this study because future studies may use only the mass of the torso, making it difficult to compare data to this study.

Another source of error for this study relates to the ARS's which were used to determine angular velocity. In examining the data for the angular velocities of the football helmets, it was suspected that a sensor in the headform may have become loose during testing. This would explain the increased variation in those tests.

Another limitation of this study is that the delay between impact may not represent some real times between gameplay impacts. Further testing may be needed with varying impact delays to more closely relate laboratory testing to gameplay. One final limitation for this study was the variation of impact speed. Although the data were normalized by the speed of the pneumatic ram, the differences in the speed of the impact may still have caused some changes in the ATD response.

Conclusion

This study showed that, in most cases, repeated impacts did not have a significant effect on a helmet's ability to attenuate impact energies. Lacrosse helmets showed more variation in kinematic responses when compared to football helmets. Future steps for this study include expanding the test procedure to include more repeat impacts and shorter delays between impacts. Additionally, for the helmets that are affected by repeated impacts, the padding components should be studied independently for improvement.

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Appendix A: Variable Name Definitions

| Sports Helmet | Variable Name | Variable Meaning |
|----------------------|----------------------|--|
| Lacrosse | RearSS | Rear Impact of Schutt Stallion Lacrosse Helmet |
| Lacrosse | RearC | Rear Impact of Cascade Lacrosse Helmet |
| Lacrosse | SideSS | Side Impact of Schutt Stallion Lacrosse Helmet |
| Lacrosse | SideC | Side Impact of Cascade Lacrosse Helmet |
| Football | RearR | Rear Impact of Riddell Football Helmet |
| Football | RearS | Rear Impact of Schutt Football Helmet |
| Football | RearX | Rear Impact of Xenith Football Helmet |
| Football | SideR | Side Impact of Riddell Football Helmet |
| Football | SideS | Side Impact of Schutt Football Helmet |
| Football | SideX | Side Impact of Xenith Football Helmet |

Appendix B: Resultant Data for Football Helmets

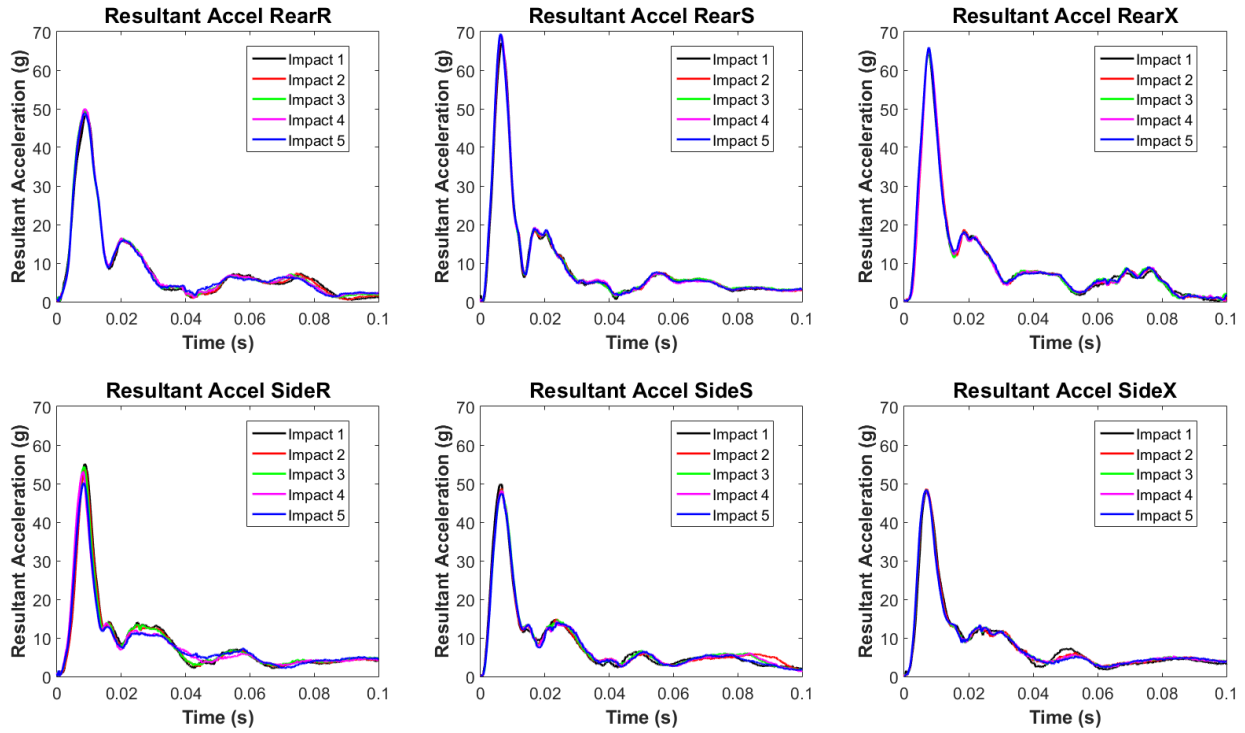


Figure B - 1: Resultant Linear Acceleration for Youth Football Helmets (Zoomed Out)

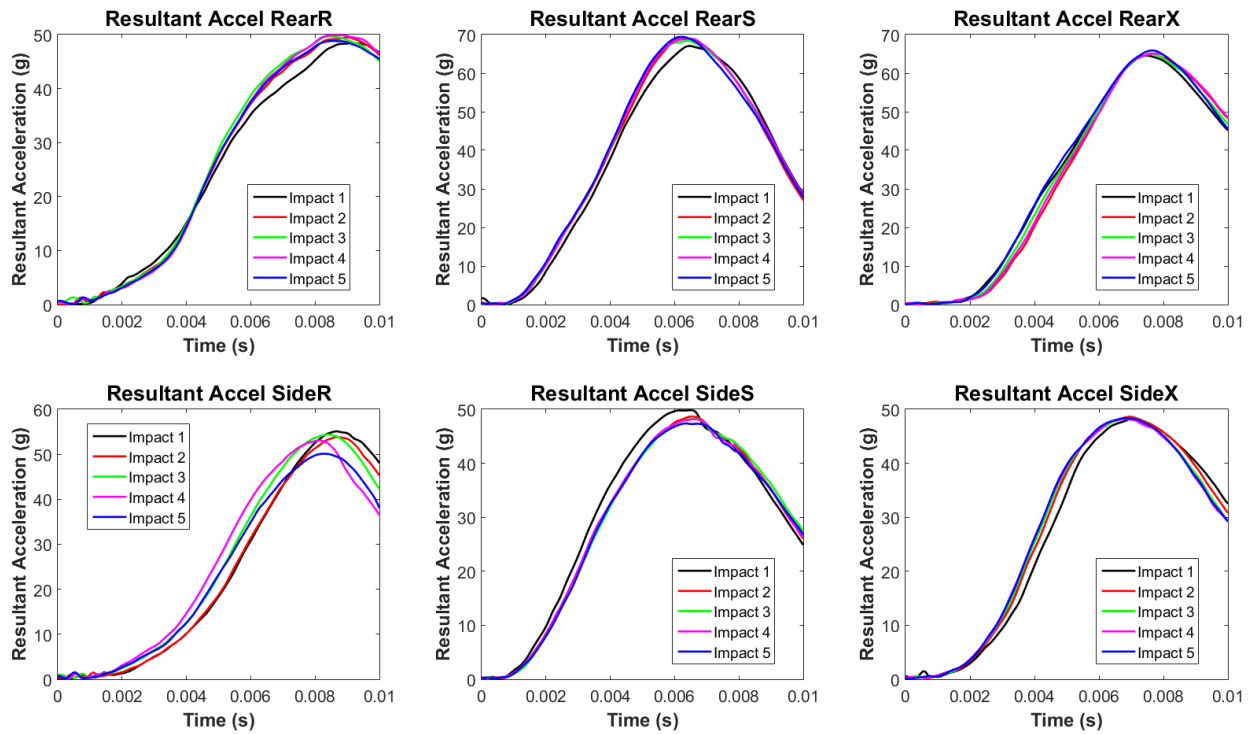


Figure B - 2: Resultant Linear Acceleration for Youth Football Helmets (Zoomed In)

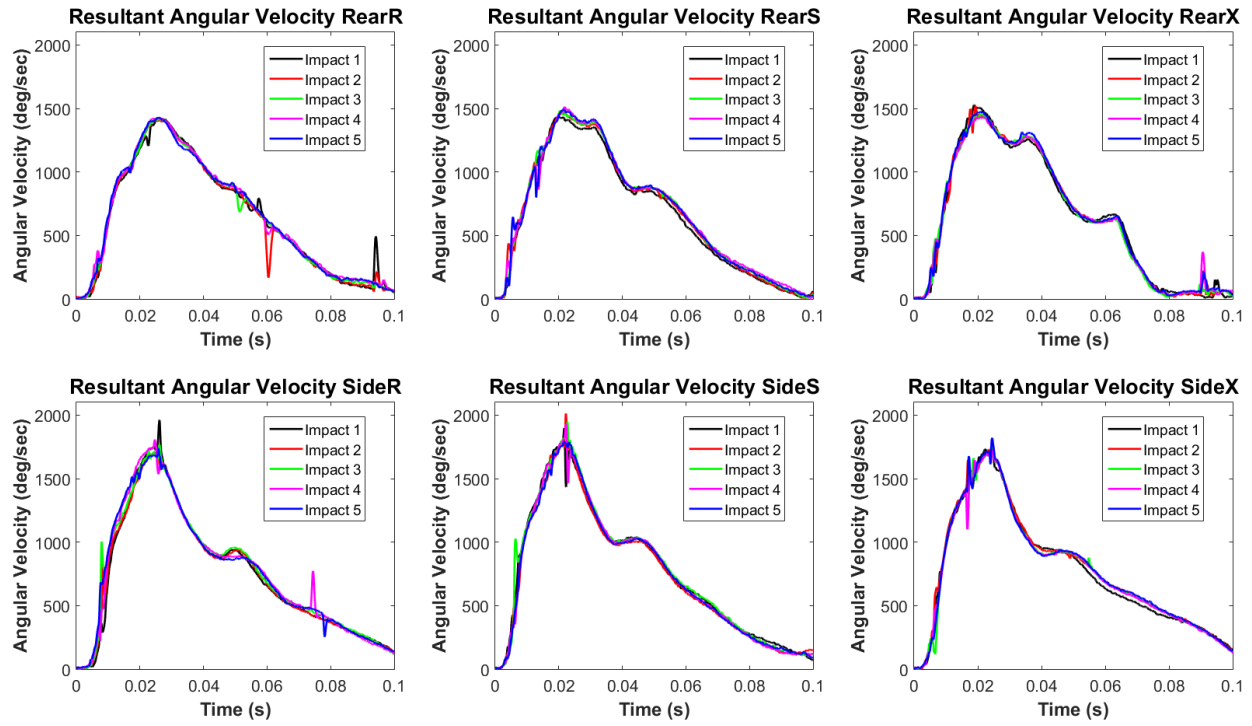


Figure B - 3: Resultant Angular Velocity for Youth Football Helmets (Zoomed Out)

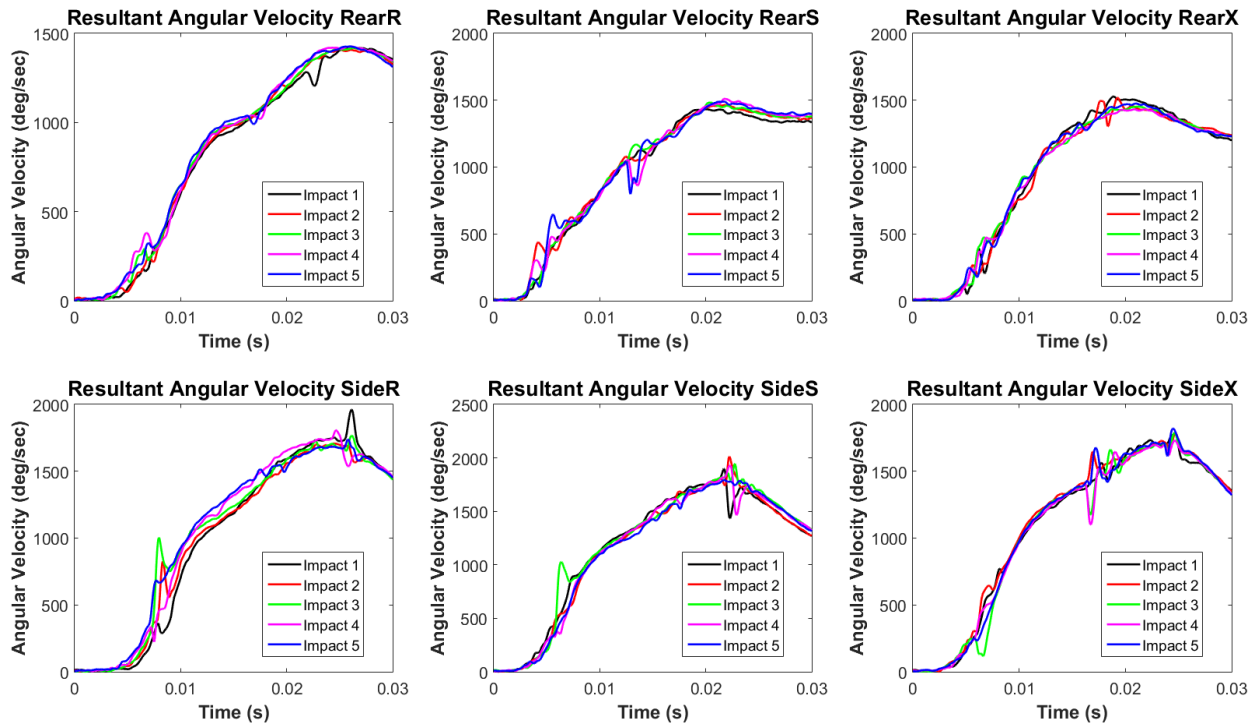


Figure B - 4: Resultant Angular Velocity for Youth Football Helmets (Zoomed In)

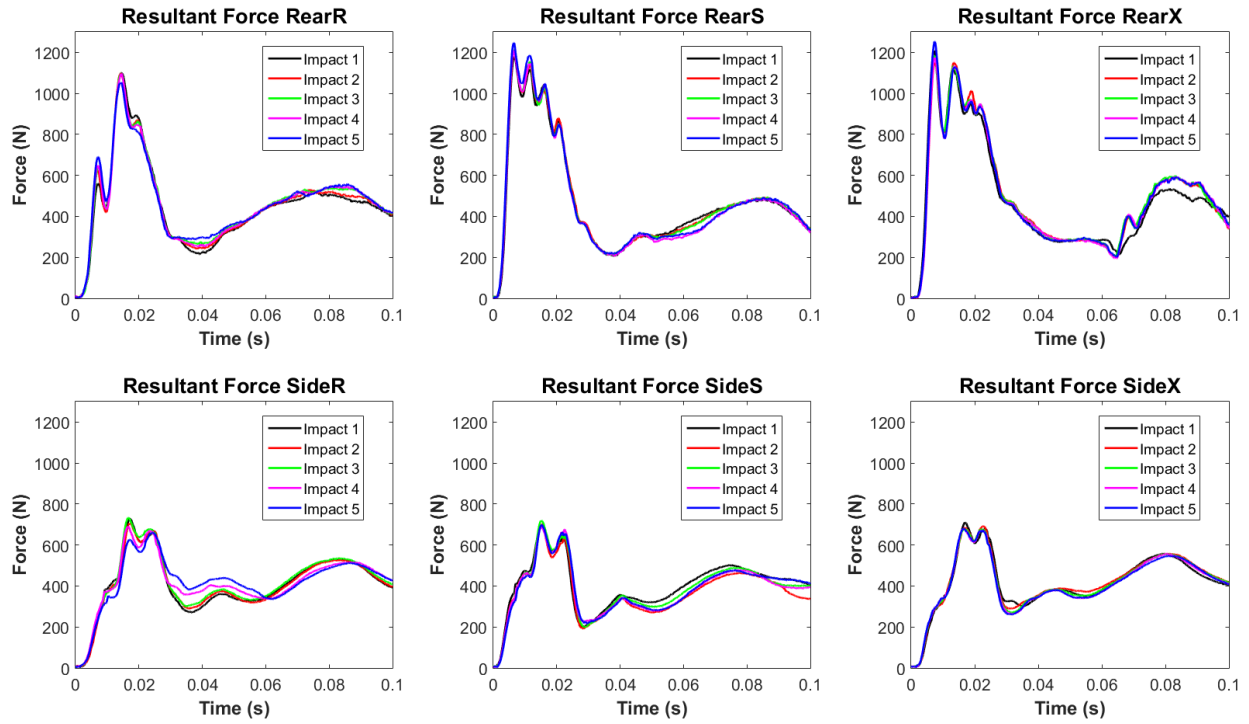


Figure B - 5: Resultant Force for Youth Football Helmets (Zoomed Out)

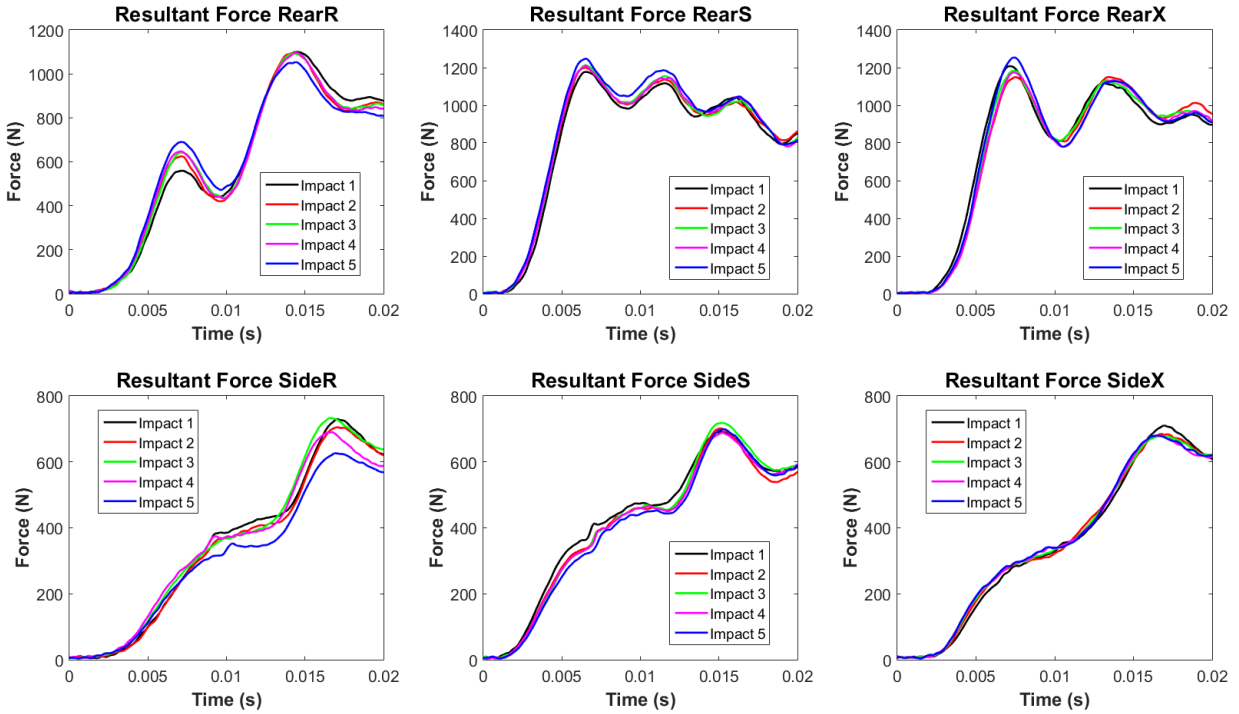


Figure B - 6: Resultant Force for Youth Football Helmets (Zoomed In)

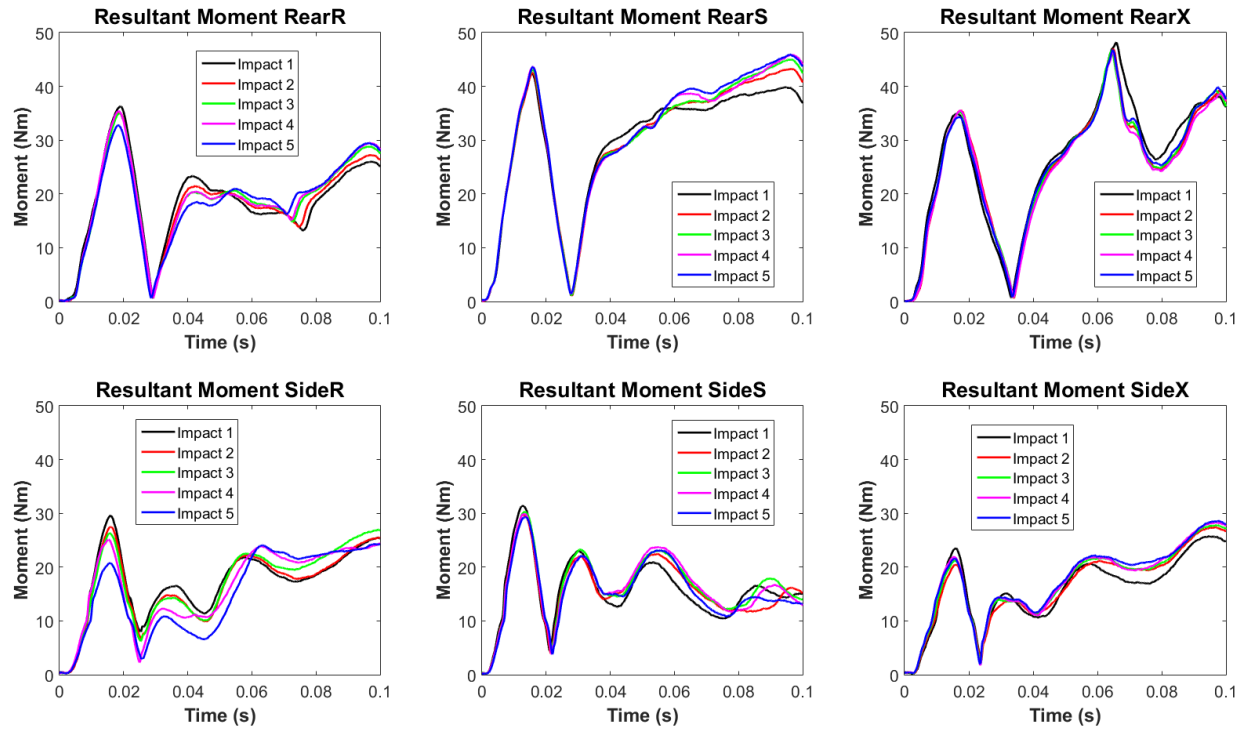


Figure B - 7: Resultant Moment for Youth Football Helmets (Zoomed Out)

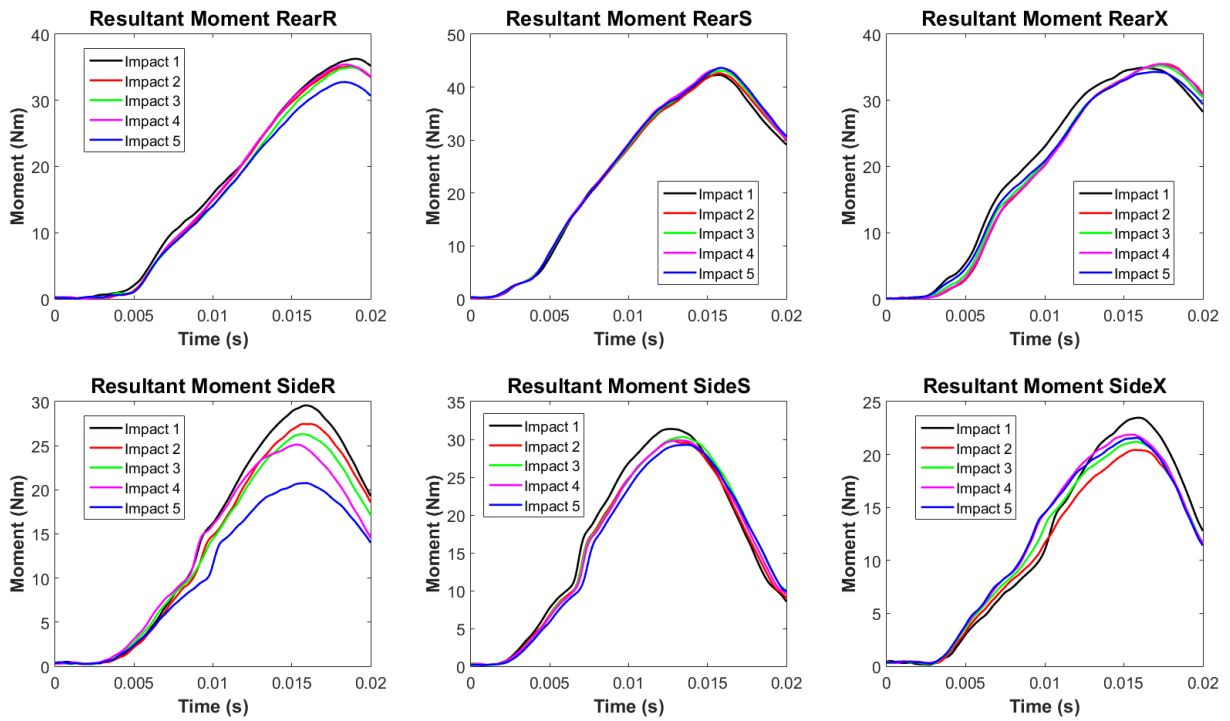


Figure B - 8: Resultant Moment for Youth Football Helmets (Zoomed In)

Appendix C: Resultant Data for Lacrosse Helmets

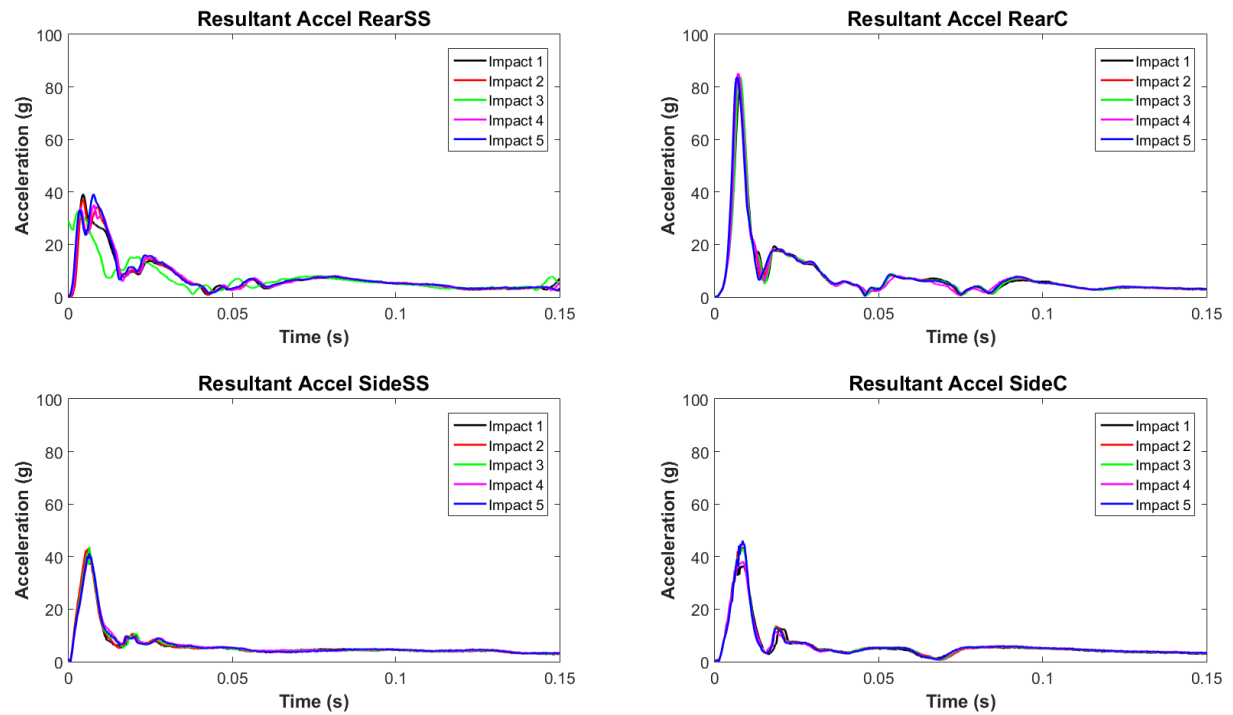


Figure C - 1: Resultant Linear Acceleration for Adult Lacrosse Helmets (Zoomed Out)

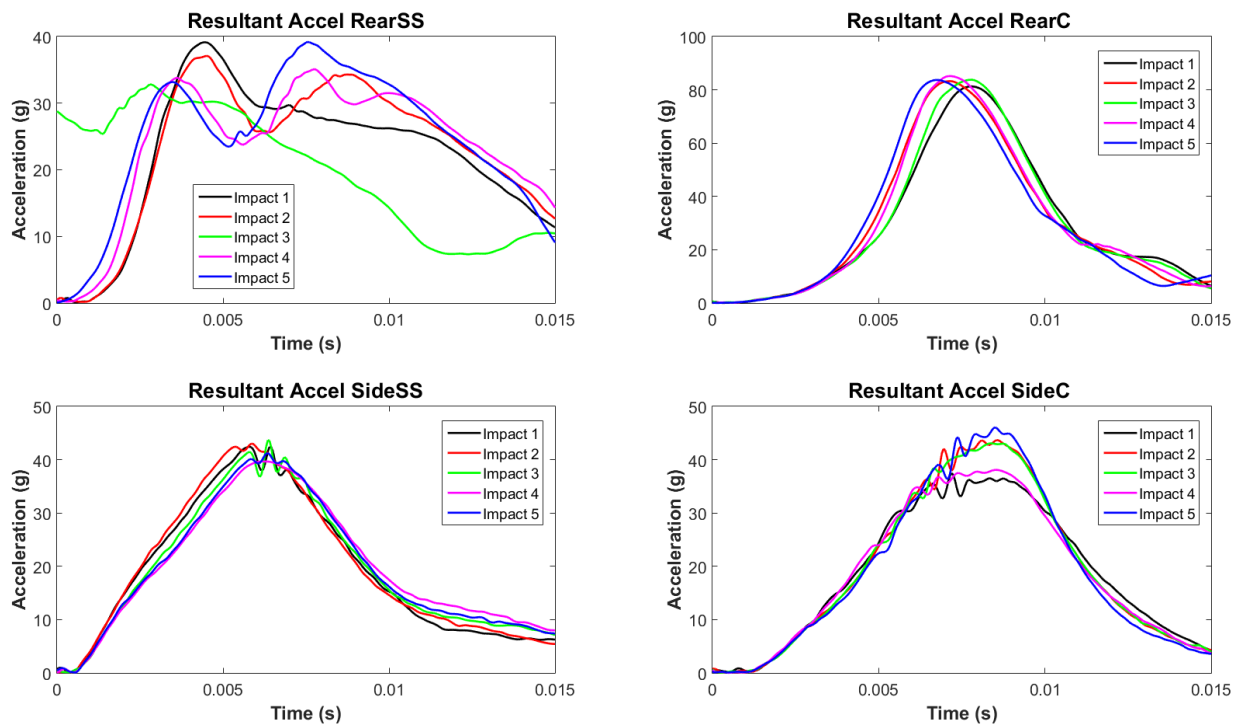


Figure C - 2: Resultant Linear Acceleration for Adult Lacrosse Helmets (Zoomed In)

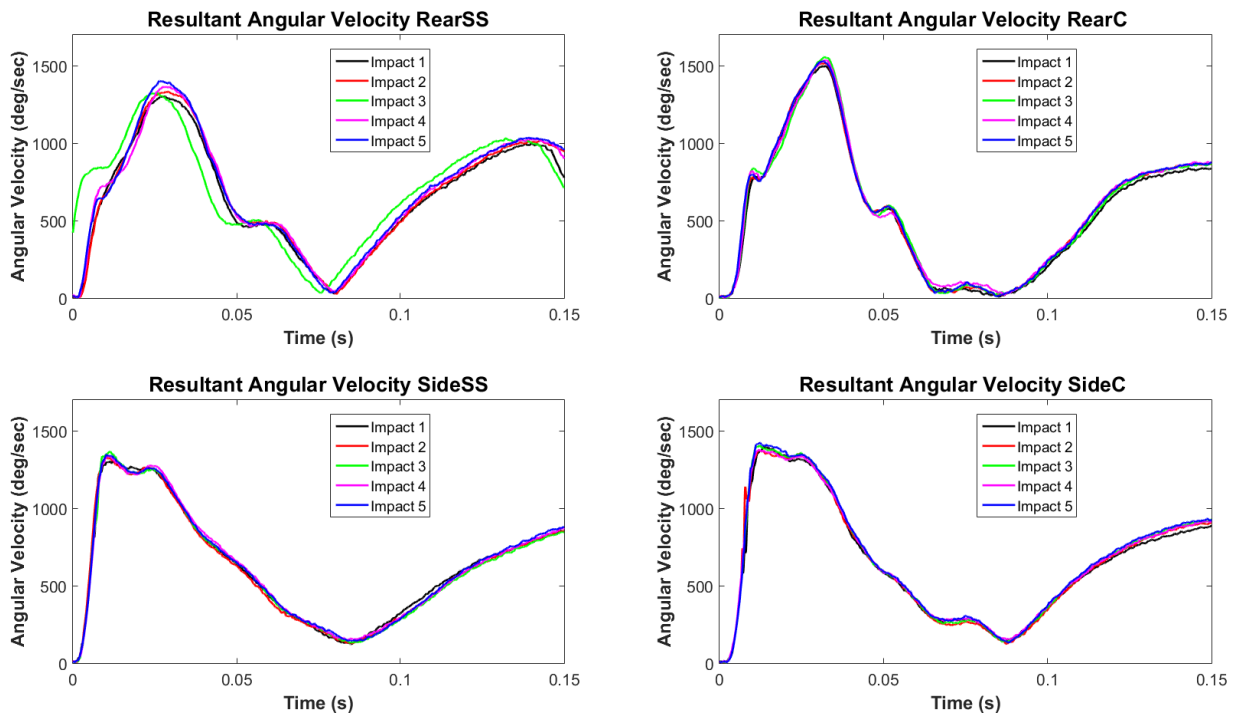


Figure C - 3: Resultant Angular Velocity for Adult Lacrosse Helmets (Zoomed Out)

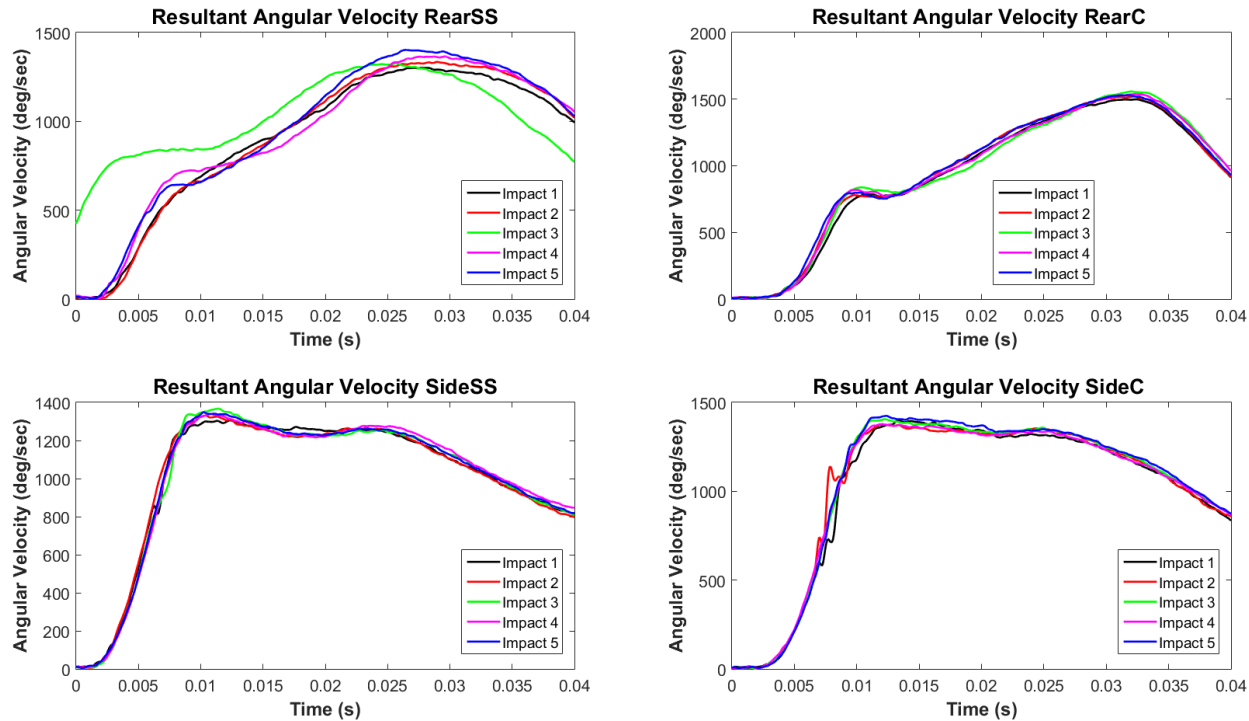


Figure C - 4: Resultant Angular Velocity for Adult Lacrosse Helmets (Zoomed In)